Design Principles for Thermally Comfortable and Low Energy Homes in the Extreme Hot-Humid Climatic Gulf Region, with reference to Dammam, Saudi Arabia

Abdulrahman Mohammed A. Alshaikh

B.Arch., M.Sc.

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بسم الله الرحمن الرحيم

In the name of Allah "the God"

the Most Beneficent, the Most Merciful

ABSTRACT

Indoor thermal comfort and its consequent energy consumption, are an increasingly important area of consideration in both developed and developing countries. The Gulf States, characterised by their composite extreme hot-humid climate and Air-conditioning dependent society are renowned for their high energy consumption. The main aim of this research is to review and report on ways to enhance occupant thermal comfort in homes through improved building and system design and use that minimises energy consumption possible, in the extreme climate of Dammam, Saudi Arabia. The thesis does this by measuring and analysing the thermal performance of the buildings, the thermal satisfaction and comfort responses of their occupants and the energy consumption in them during August 2013 for the summer period and January 2014 for the winter period of the study. The comfort of occupants was assessed using the adaptive thermal comfort method. Neutral indoor air temperatures were, in several homes, surprisingly high. Moreover, most of the studied dwellings do not represent thermally comfortable homes as defined within either PMV or adaptive comfort limits. The study went on to review a broad range of factors that might strongly influence neutral temperatures indoors including the properties of the dwellings, occupant behaviours and attitudes towards high energy demand, loads and costs. The findings are discussed and conclusions drawn on individual design features that contribute to the comfort or discomfort experienced by occupants. It was found that lifestyle, attitudes and other socio-cultural factors have a clear influence on the comfort and in turn energy use in individual dwellings. Although several respondents did not sincerely care about the electricity as it is cheap, in late 2015 the Saudi government hiked the price of domestic energy bills by 60% as a result of low oil prices, putting pressure on many ordinary families to take more notice of their day to day living expenses. The recent electricity price hike provides an economic impetus for the design guidance proffered in the conclusions of this thesis to be taken seriously by householders and implemented by both them and regulating authorities in order to enhance domestic buildings and in turn reduce the CO_2 emissions to the global atmosphere. The conclusion of this study is broadly applicable to other regions with similar climatic conditions and cultural contexts such as the Gulf countries.

DEDICATION

I dedicate this thesis to my family especially:

My father who taught me how ambitious I should be; he is my inspiration for everything.

My mother who surrounded me with her love, praying for me throughout the time I spent working on my thesis.

With a special dedication to my lovely wife and my children (Reem, Shahad, Mohammed, and Yousif) being a great part of my success

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CHAPTER ONE: INTRODUCTION

"The more important reason is that the research itself provides an important long-run perspective on the issues that we face on a day-to-day basis"

Ben Bernanke

Energy services are a crucial input to the primary development challenge of providing all the necessities for living, including food, shelter, clothing, water, sanitation, medical care and schooling, with their role recognised in supporting the provision of the primary needs for all aspects of comfortable living. However, since the noticeable, continuing decline of non-renewable energy resources all over the world, and the growing awareness of global problems such as the impacts of the built environment on climate change and environmental degradation, there is a growing global scientific agreement on the need to reduce energy consumption in buildings. Over the past few decades, buildings have been recognised as a key contributor to global energy consumption, accounting for around 40% of the world's energy consumption (Ghiaus and Inard, 2004, cited in Hammad and Abu-Hijleh, 2010 P:1888). Buildings are also accountable for around the half of the total global carbon dioxide (CO_2) emissions (Roaf et al., 2010), not to mention that some evidence suggests that climate change and global warming are the results of anthropogenic discharges of greenhouse gas emissions from buildings (Karl et al., 2009).

Responding to these issues, there is also substantial interest in many developing countries in moving towards ecological building solutions in order to protect the environment. These solutions involve addressing both energy and environmental concerns, by creating climatically responsive buildings that succeed in delivering adequate internal conditions with less environmental impact. Additionally, as climate differs by latitude and altitude, suitable architectural solutions for the particular place have to be contrived (Roaf et al., 2013). Vernacular architecture built by local people has been proved to be responding closely to the sociocultural requirements (Givoni, 1998), as it offers architectural solutions for their ecological niches (Roaf et al., 2013), and is expected to be an inspirational source for today's architectural practice. Although many studies have been published so far on how to reduce buildings' emissions by integrating renewable energy systems from a mechanical and constructional point of view, standards of thermal comfort and its association with occupants' behavioural strategies are very seldom studied (Roaf et al., 2010).

Additionally, due to rapidly escalating populations on most of the world, on one hand, and high economic growth levels on the other, the world is experiencing, in many regions, critical infrastructure expansions that are often challenging to manage. With the rapid climate change becoming manifest also in many regions resulting both from upsurges in emissions and accelerated natural effects like the El Nino effect, the human species may struggle to survive (Roaf et al., 2009). Politicians around the world are aware of the imperative of taking immediate action to oppose the consequences of serious hazards for future generations and the move towards low carbon buildings is widespread as is the move to running them of renewable energy sources such as solar technologies. However much of the current legislation pays no attention to the role of occupants in reducing energy consumption while at the same time achieving sufficient thermal comfort in contemporary buildings. As a consequence, the trend towards counteracting the warming climate being framed largely in term so of conventional mechanical technologies is almost universal resulting in very high energy demand in air-conditioned buildings appears to be rapidly rising (ibid), particularly in very hot regions such as Saudi Arabia.

This chapter provides a brief rationale on the significance of reducing energy consumption in domestic buildings and goes on to presents a statement of the problems concerning energy consumption in Saudi Arabia and the related critical issue providing thermally comfortable conditions in homes there. The consideration in this thesis of the Saudi Arabian context, led to the formulation of the research questions for the study as well as the aims and objectives of this research. The following sections of the chapter presents an outline of these aspects of the research, along with aims and objectives of the research question and a summary of the thesis structure.

1.1 Domestic energy consumption

The patterns of global energy consumption depend on local climatic conditions, the culture of the citizens and the policies of the individual country (Reddy, 2000). It is posited that to investigate a community in order to help to reduce energy consumption in buildings, many factors should be taken into account, including the building's location, the local culture and climate conditions and the occupants' needs (OTA, 1979; Reddy, 2000; Smith, 2008; Roaf et al., 2009; Hawasly et al., 2010). Only then it is feasible to establish locally relevant standards for the individual location, society and economy, that define the range of energy consumption levels in domestic buildings in kWh/m² that can be deemed as low, or very low, based on the above characteristics. Recently, the term 'low carbon energy buildings' has been commonly used by architects to reflect design choices intended to reduce the impact of the construction on the environment. It is claimed to be possible for low energy buildings to reduce certain operational building costs by as much as 80% through the application of integrated design (LBEE, 2009).

Low energy buildings are buildings, with a predicted or measured better energy performance when compared to local standard ones are often characterised by features such as high performance insulation types and levels, energy efficient glazing and energy efficient technologies for heating and cooling systems (ibid.) and so on. At present, seven European Member States have adopted a working definition of low energy housing, which is mainly applied to new houses, but also covers existing houses, and can usually apply to both residential and non-residential buildings (LBEE, 2009). The required reduction in energy consumption normally ranges from 30% to 50%, which corresponds to a resulting annual energy demand ranging from 40 to 60 kWh/m^2 in central Europe. Scotland has been even more ambitious aiming for zero carbon buildings in addition to 100% renewable energy by 2030 (Gilchrist et al., 2013); however, what is considered a low energy development in one country may not meet local definitions in another country.

1.2 The problem in Saudi Arabia

Saudi Arabia is a rich oil producing country, benefitting from its highly developed oil and gas exporting economy on which it a highly dependent. It is also a country characterised by high energy consumption rates in the built environment. The hot climate in the region and the corresponding operation of air conditioning systems explains, to a large extent, the high levels of energy consumption (Taleb and Sharples, 2011). Future projections, moreover, reveal an even more alarming prospect for the country. Energy consumption in the form of electricity has increased sharply in Saudi Arabia, over the last two decades (Alyousef and Stevens, 2011). This increase is due to the rapid development of the economy in the absence of energy conservation policies. In 2001 the peak load reached around 24GW, which was around 25 times that of 1975, and it is expected to reach 60GW by 2023 (Al-Ajlan et al., 2006). In economic terms, consequently, the total investment required in order to meet this demand could exceed £ 61 billion (ibid). However, although this huge consumption of electricity for buildings is, in fact it does represent a major potential for reducing energy consumption (Fasiuddin and Budaiwi, 2011). However, ‘energy consciousness’ continues to be virtually absent in the developing world, and this also pertains not least to citizens in Saudi Arabia.

The architectural practices, which will be described later in the literature, together with the rapid population growth, the economic development, and the consequent rapid increase in energy demand in the form of electricity, has taken place over the last 25 years in Saudi Arabia (Al-Ajlan et al., 2006). According to the Saudi Ministry of Water and Electricity (MOWE, 2014), the energy sold to residential subscribers in 2014 was 135,908 GWH, which is almost half of the total energy sold (49.8%) for all sectors, and this quantity is increasing annually by 6.9%. The population of Saudi Arabia, on the other hand, reached 30,770,375 in 2014 and is likely to reach 37,610,985 by 2025. This rapid increase will result in further energy demands to operate new domestic buildings, with a consequent economic and environmental cost. Taking into account that there are projected to be 2.32 million further new homes in the Saudi market by 2020 (Ahmad, 2002), a significant increase in the electricity supplied for residential buildings will be needed in the coming years.

Summertime indoor conditions in Saudi homes are of increasing concern, due to the potential for increased discomfort and higher energy costs resulting from more extreme outdoor weather. During summer, outdoor and indoor discomfort are exacerbated during extreme hot spells, particularly when dust storms occur, which prohibit the use of natural ventilation as well as reducing the efficiency of AC systems. The rise in the occurrence of abnormally hot spells experienced in the region during summers and the transition seasons signal the emergence of a climate that is less predictable and more adverse throughout the year (Tanarhte et al., 2015). Therefore, the indoor experienced conditions will inevitably become chronic during extreme hot spells and outages, due to the fact that all contemporary buildings in Saudi Arabia have been primarily designed to be cooled artificially to provide adequate indoor conditions (Eben Saleh, 1998).

Given that air-conditioning accounts for 70% of the power demand from residential buildings, the electricity generation capacity has doubled in the last decade to around 50,000MW (MOWE, 2012) but still struggles to keep up with the cooling demand in summer, which rises by as much as 50% at peak periods. Air-conditioning is the crucial factor in this peak, leading to some regions suffering systematic power outages, with serious health consequences when temperatures reach 40-50 degrees Celsius and even over that. In the last few years, the pattern of outages follow is that they occur frequently and at times of peak demand. Prior to summer 2013, a headline in the Alriyadh newspaper in Riyadh reported a statement by the head of the electricity company “no promises not to have outages during this summer in the afternoons” (Alahmad, 2013). Account needs to be taken of the fact that the historically low energy prices in Saudi Arabia have encouraged higher energy demand by consumers (Alyousef and Stevens, 2011). A 60% hike in Saudi Arabian domestic energy prices (MOWE, 2015) from December 2015 is predicted to disproportionately affect energy costs in low-performance homes, which will consequently put financial pressure on some Saudi households.

Rising indoor temperatures must eventually drive higher levels of discomfort, which in turn will put a growing financial burden on families, impacting adversely on their lifestyles and standards of living. Similar pressures were key drivers in the collapse of the US and subsequently global economies in 2007, when American homeowners found that rising energy bills meant they could no longer pay their mortgages, providing some evidence that if not dealt with, this too could be a major problem for Saudi Arabia (Roaf, 2014). Since the last world economic crisis, the cost of living has risen remarkably in the region, putting households under increasing financial strain to spend more while the income levels remain the same (Albaaz, 2008), with the rising cost of electricity over the last decade making up a considerable portion of the growing wedge between lifestyle aspirations and affordability.

In view of the high domestic energy consumption in Saudi Arabia, alongside the cooling demand due to hot climates, serious steps are urgently needed in order to reduce domestic energy consumption. The development of low energy home codes and establishing energy consumption standards based on local climate conditions and citizens' needs is fundamental; such codes are absent in Saudi Arabia and are essential to control the national energy consumption. Moreover, in Saudi Arabia and almost all the gulf countries, research work on thermal comfort is still an undeveloped area to be explored. In light of the increased awareness of the global and local imperatives for energy saving in homes, the role and importance of thermal comfort in achieving energy reductions is increasingly recognised and valued to shape the development of the research questions and methodology at the heart of this thesis.

1.3 Research hypothesis and questions

A question underlying this research concerns the extent to which the experience of thermal comfort in homes in Dammam is very different from that in homes in other countries. The core premise of this study is that the degree of comfort experienced in homes in Dammam results both from the characteristics of the performance of the individual homes themselves and the occupant's behaviour that results from the degree of physical and mental adaptation pertaining to the individual concerned. It is postulated that both these factors can either lead to badly performing homes which consequently results in a poor comfort experience (or vice versa), high energy consumption and costs and huge knock-on environmental and economic costs and or benefits across the region. Furthermore, the range and scale of adaptive opportunities in the design of a building will influence the ability of the individual to manage and control the conditions they occupy and the result energy consumption used to achieve them. A number of research questions have been designed as a basis upon which to develop the following research plan and methodology. The key question that this study will address is**:**

What opportunities exist in homes in Dammam to improve comfort, while not increasing energy use?

The research question will be addressed by the following sub-questions:

1. What indoor conditions are experienced and what levels of thermal comfort are currently achieved in existing dwellings in Dammam?
2. What are the range and norms of energy consumption and the operational costs in Dammam's homes today?
3. What characteristics of the Dammam dwellings enhance the thermal experience and lead to lower operational cost?
4. What adaptive opportunities are there for the individual homes/occupants' behaviour to be improved in order to enhance the thermal experience as well as reducing energy consumption?

1.4 Research aim and objectives

The main aim of this research is ***"to help occupants achieve thermal comfort through the improved design and use of dwellings, with the least energy consumption possible, in the Eastern region of Saudi Arabia."*** To achieve this aim, a number of objectives have been identified and summarised as follows:

- People and comfort:
  1. To investigate how thermal comfort is currently achieved in existing dwellings in Dammam.
  2. To determine and compare the neutral temperature of people living in Dammam's dwellings.

3. To identify some of the adaptive behaviours used by people to ensure comfortable conditions.
4. To find out the difference between occupants' usage in terms of the AC system operating times throughout the day and year.

- Energy consumption:
  5. To investigate the average energy consumption in typical existing homes in Dammam and the operational cost of cooling dwellings.
  6. To investigate the factors impacting on energy consumption and in turn affecting the thermal experience in existing dwellings.
  7. To analyse the performance of different types of dwellings in order to characterise comprehensive guidelines for the optimisation of more efficient design.
- Dwelling design:
  8. To explore the range of adaptive opportunities of the individual homes that can be exploited to achieve comfort.
  9. To find out what opportunities exist for homes to be altered and retrofitted in order to reduce energy consumption.
  10. To make recommendations on key strategic design features that could be incorporated into the houses of Dammam to ensure comfort while minimising energy use over the year.

From this work it is hoped to provide a theoretical basis for introducing the thermal comfort regulations in Dammam, Saudi Arabia.

1.5 Structure of the thesis

Chapter 1 Introduction: This is the starting point of the research. This chapter has presented the background to, and an overview of the research field, offering a statement of the problem in the case study location Saudi Arabia and explaining how developed countries are dealing with this issue. This chapter has also presented the main aim, objectives and research questions.

Chapter 2 Literature Review: This chapter divided into two sections: the first part presents a background and overview of Saudi Arabia; the second part is devoted to a review of recent studies and research related to the subject of thermal comfort, and briefly mentioned design solutions that contribute to building performance. It also covers important issues and aspects investigated in the research, together with details of the background to the many different studies covered in the literature review to support the research in this field.

Chapter 3 Research methodology: This chapter describes the research plan and approach used to achieve the proposed aim and objectives. A number of approaches are presented to provide a clear indication of the chosen methodology and variables measured, which are important in any thermal comfort study. This chapter describes the main methods and tools of data collection that were employed by the researcher in order to arrive at certain results and/or objectives, including measurements of individual parameters, and the scales and questionnaires.

Chapter 4 Field work procedure and data collection: This chapter of the thesis aims to achieve the proposed aim and objectives in studying the factors that influence thermal comfort in domestic buildings in Dammam. It focuses on two aspects: the first part highlights the procedure of the fieldwork; it describes the fieldwork plan and describes the building samples. The second part will briefly define the results that were collected from the occupants in their homes during the subjective survey, by means of questionnaires.

Chapter 5 Findings and data analysis: This chapter is concerned with the data that were collected during the field survey. The first section highlights the results gathered during the subjective study from the occupants in their homes, using the questionnaire. The second section of this chapter analyses and evaluates all the available data, including all measurements for thermal comfort requirements collected in the form of subjective and objective data, which are described in detail. The analysis includes an overall description of the general questionnaire, the transverse survey and the longitudinal survey.

Chapter 6 Differences between dwellings: this chapter explores the differences between different dwellings, particularly in the hot season, by classifying individual buildings by performance and the more noteworthy dwelling in terms of their performance are analysed in-depth. The analysis begins by highlighting the factors that characterise the dwelling, including its location, orientation, age, size, material, insulation and the type of mechanical ventilation used, together with some comments of the informal interview. It then presents the demographic information regarding the dwellers and the available data on their daily behaviour. Finally, it presents a summary of their energy bills over the year and the cost of energy per square metre of each dwelling.

Chapter 7 Discussion: This chapter explores the designs and adaptive opportunities available for low energy homes appropriate for Dammam residents. The discussion is based on the results of the investigations in the previous chapters and is related to the literature outlined in Chapter Two, regarding how to provide indoor thermal comfort while keeping energy consumption to a minimum. In order to provide useful guidance on how to improve a dwelling's performance, it is necessary to describe and discuss in depth the design opportunities available, along with the ways in which occupants can adapt their dwellings in order enhance the dwelling's performance.

Chapter 8 Conclusions: This chapter summarises the research findings and presents a summary of how the established research questions have been answered through the research stages. This chapter presents an account of how the main aims of the research have been met, as well as the limitations. Finally, it describes the future work to be carried out by the researcher and provides recommendations for future researchers, as well as decision makers, architects, developers and homeowners.

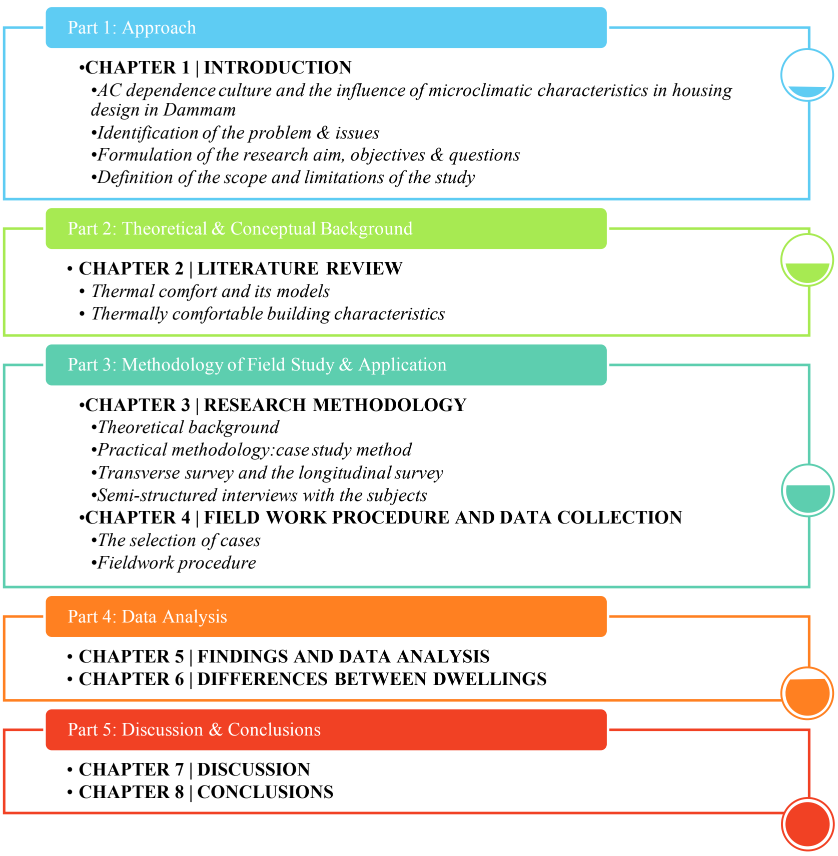


Figure 1.1 Diagram of the structure of the thesis.

CHAPTER TWO: LITERATURE REVIEW

"Summer afternoon -- summer afternoon; to me those have always been the two most beautiful words in the English language."

Henry James

2.1 Introduction:

Reportedly, around 40% of the world's energy consumption is accounted for by building use, which contributes half of the total global CO_2 emissions (Ghiaus and Inard, 2004, cited in Hammad and Abu-Hijleh, 2010 P:1888). Reducing energy use in buildings thus addresses both energy and environmental concerns. However, low energy building construction is very seldom even discussed let alone implemented to date in Saudi Arabia, where the modern, fashionable design archetypes demand a significant consumption of electricity for air-conditioning requirements, not only due to the extreme hot climate but also to design faults in the model. Poor energy performance in homes may on one hand be due to the characteristics of an individual building, and or to the behaviours of its occupant's behaviour. Consequences of poor energy performance within homes can consequently result in rising indoor temperatures, poor levels of thermal comfort experienced, higher energy bills and environmental impacts. Conversely well performing buildings result in both energy conservation as well as positive thermal experiences.

This chapter comprises two sections: an overview of Saudi Arabia context and then a literature review on thermal comfort. In the first, the context of the research is clarified through a brief historical overview of Saudi Arabia. It provides a background to, and grounds for reflection on, the contemporary problems of the factors that have influenced the formation of the existing housing conditions. The second part is devoted to a review of recent studies and research related to the subject of thermal comfort and discusses design solutions that can contribute to energy conservation.

2.2 Saudi Arabia - an overview

At the intersection of Asia and Africa, the Arabian Peninsula is located in the southwest corner of Asia. The kingdom of Saudi Arabia occupies about four-fifths of the Arabian Peninsula, with a total area of around two million square kilometres (Central Department of Statistics and Information, 2008). Saudi Arabia is bounded by the Red Sea to the west and Arabian Gulf in the east, and has land boundaries with Qatar and the United Arab Emirates alongside the Arabian Gulf, and Jordan, Iraq, and Kuwait in the north, Oman, and Yemen in the south. Because of its large area and topographic variation, the natural setting of the country can be split into five areas in terms of topography. The Empty Quarter is desert, and other deserts in the Central and Northern

Regions take up almost half of the area. The central plateau, the Najd, approaches 32% of the total area. The Hejaz and Asir highlands are around 7%. The eastern coastal and the northern region take approximately 5% and 4%, respectively. Tihama and the western coastal plain make up about 2% of the total geographical area. In the Empty Quarter, great sand deserts, the Nafud and Dahna, played a part in restricting the initial places of residence in the country. Consequently, the early settlement patterns and population distribution were limited to the Hejaz, Asir highlands, Tihama and the western coastal region. In the eastern part of the country, the wetlands or "*sabkha*", which is a salt-encrusted shallow basin with a soft sand surface (Vincent, 2008), along the eastern coastline region, limited the possibilities for establishing new communities there (Al-Hathloul and Edadan, 1995).

Figure 2.1 Map of the Kingdom of Saudi Arabia showing the administrative provinces, and the location of Dammam in the Eastern Province (Adapted from: Vincent, 2008)

Nowadays, the Kingdom of Saudi Arabia is divided into thirteen provinces (Figure 2.1). In terms of urbanisation, the western part of the country, which contains the Makkah and Madinah administrative regions, is the most developed part of the country, followed by the Riyadh area (Al-Hathloul and Edadan, 1995). However, there has been a great deal of development in the Eastern Province since oil production began in the late thirties, which led to high growth rates in the urban population (Al-Shuaiby, 1976; Al-Hathloul and Edadan, 1995). Owing to the discovery of oil, the eastern region, in particular, brought great opportunities to the country; hence, it is unlike other Saudi cities in terms of its historical roots (Al-Shuaiby, 1976).

2.2.1 *The population and the growth of the housing sector*

Turning to the population of Saudi Arabia, according to the population records of the Central Department of Statistics and Information (CDSI), the total population of the Kingdom has increased from roughly seven million in 1974 to around 30.8 million in 2014, with an average growth rate of 4.2% (MEP, 2014). This has inevitably led to an increase in the demand for homes during the period. Data from CDSI shows that demographic surveys conducted in 2010, did not reveal a substantial change from previous statistics in the number of Saudis owning their homes, which was nearly 50% of the population, making up approximately 2.7 million households. It was also shown that around 40% and 10% of Saudi families lived in rented units and units afforded by employers, respectively (ibid).

In addition, it is estimated that by 2019 Saudi households will increase by 750 thousand, and there are projected to be 2.32 million further new dwellings needed in the Saudi market by 2020 (Ahmad, 2002), to cover the shortage of the existing accommodation and future needs. Therefore, around £1.8 billion from the excess government budget has been appropriated for the housing programme. The number of dwellings required means the housing authority gives a high priority to field studies into affordable and economic housing, not to mention the architectural competitions held at universities and architectural offices to improve such housing projects. However, progress in this area is still below aspirations, despite the efforts of various organisations concerned with the housing sector.

2.2.2 *The Eastern Region of Saudi Arabia*

The geomorphology landform of the Eastern Region is described as moving sands, together with *sabkha* (salt flats) and limestone scarps (Barth and Böer, 2002). The *sabkha* are common along the coastline between Kuwait and the southern end of the Arabian Gulf. Coastal *sabkha* alternate with flat and extensive sand sheets and inactive dune systems from Kuwait to the area north of Dhahran, which includes Dammam city.

Historically, this area of the country consisted of small fishing villages of unsettled nomadic tribes living in tents, as well as a few settlements consisting of traditional houses and shelters (Al-Naimi, 1989). However, the discovery of oil was the breakthrough that has enabled the region to continue its growth and expansion, and plan new cities (ibid). Many cities (for instance Jubail) have been built entirely from scratch since the 1950s, and this extensive development has resulted in several modern and well-developed cities (Al-Shuaiby, 1976; Talib, 1984; Al-Hathloul & Edadan, 1995; Zahid, 1996; Al-Hathloul & Aslam Mughal, 1999; Eben Saleh, 2001). However, the architectural history of Dammam has left very few records of the region's past, except for some ruins which stood offshore until the late 1970s (Dammam Municipality, 1993) (Figure 2.2).

Figure 2.2 On the top left, an aerial view of Dammam (26.4° N, 49.9° E) in 1935 shows the compact traditional pattern (Source: MMRA, 2012); on the top right, an aerial view of Dammam in 1962 shows the emergence of the modern gridiron planning pattern beside the compact traditional Al-Dawaser neighbourhood along the sea shore (Source: Al-Shuaiby, 1976); below, the up-to-date aerial map of Dammam city with the traditional Al-Dawaser neighbourhood circled in red. (Source: Google Maps, 2016).

2.2.3 *The transformation from traditional to contemporary housing*

In the period of the 1950s, due to the shortage of professional planners in the country during the forties, planners from the Arabian American Oil Company (ARAMCO) were officially commissioned to design many neighbourhoods in the oil exploration region (Mahmud, 2009). This was followed by another plan in 1979 by the Hill International Consultant Engineering company (CH2M) to develop roads and houses in both Dammam and Alkhobar city (Al-Naimi, 1989) which is shown in Figure 2.3.

It can be seen that the American model forms the main characteristic of these new developments. As a result of a shortage of skilled local labourers, a variety of expert professional and skilled labourers from different parts of the world were required to build the desired modern cities (Al-Naim, 2008). Consequently, there was a noticeable acceleration of the migration of international and domestic workers into the region (Mahmud, 2009).

Literally, almost all pre-1950s dwellings in Dammam region were demolished and replaced by other modern dwellings, and although some of these older dwellings survived until the late seventies, they were occupied only by low-income families, that could not afford the modern transformation on that period. (Mahmud, 2009). Alongside the rapid developments in the 1950s and 60s, the requirement for housing had augmented radically and the government could not control with it. Consequently, many people began to adapt themselves to that situation and made temporary shelters by reusing wooden containers thrown away by ARAMCO (Al-Naimi, 1989), see Figure 2.4. This was entirely due to the need for a place to live in using the cheapest, easiest, and quickest method to get a home. A few years later, the government released the first building regulations alongside an announcement of interest free loans (MEP, 1965) to encourage people to build new, permanent homes. Then, and due to the high demand, an introduction of modern materials has arisen and people built their dwellings using a mixture of concrete blocks and cement for the main structure and external walls, while using wood for the roof (Al-Naimi, 1989). However, both these types of shelters have now disappeared entirely and do not exist anymore in Dammam metropolitan city.

Figure 2.3 The gridiron master plan of Alkhobar city in the Eastern region, developed by ARAMCO during the seventies (Source: MMRA, 2012)

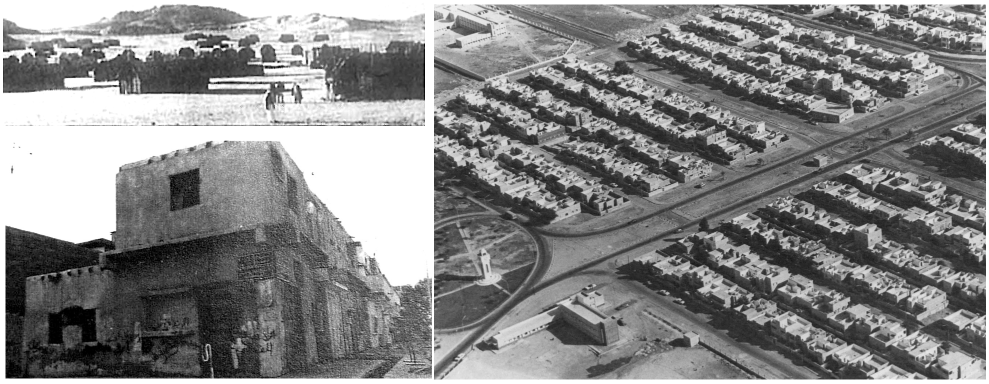


Figure 2.4 Top left: fishing camp near Dammam during the thirties (Source: Al-Naim, 2008); lower left: examples of the transitional houses in Dammam during the fifties (Source: Al-Naimi, 1989); on the right, in the sixties, the emergence of the American villa type in the residential site for exploration employees. (Source: Al-Shuaiby, 1976)

One of the main significant changes that happened after the new building regulation in the design of contemporary housing is the “extroverted courtyard” (Al-Shuaiby, 1976). The extroverted courtyard (or set back) requires all buildings to be set back a specific minimum distance from the plot boundaries, thereby ensuring passageways around the house, daylight from four sides, and separation from neighbours’ houses. Logically, the extroverted courtyard allows the heat generated by air conditioning machines to escape from the house, and enables the house to have more windows on all sides in order to get more natural light and ventilation. However, its capacity for passive cooling is very limited, making mechanical air conditioning essential if the house is to provide a comfortable interior climate. Additionally, these regulations are somewhat to blame for increasing the energy consumption in buildings as well as for “encouraging unhealthier, less comfortable buildings” (Roaf et al., 2010), as they push architects and builders towards designs which require significant use of air-conditioning.

Table 2.1 A comparison between the pre-fifties and the contemporary houses in the Eastern region.

	Pre-1950’s Houses	Contemporary Houses
Design	Was a result of the people's actual needs and reflected the interaction between economic, religious and cultural constraints, and climatic conditions.	Based on pre-planned concepts and not necessarily reflecting religious, cultural and climatic interactions. The size of the villa and its number of rooms and their functions depends on the family income and social status.
Privacy	Every house consisted of two main parts- the private part where the family's activities occurred, and the semi-private part where the guests were entertained	It is in somehow remain the same and it is not differentiated by social purpose
Orientation	Introverted courtyard house and all rooms were oriented towards a courtyard and so had an inward looking layout. A covered aisle or gallery surrounded the courtyard and an area for sitting outside.	Extroverted villa: all rooms are grouped and surrounded by a large hall used mainly as a family sitting area or for internal circulation.
Ventilation	Wind vents were located on the parapet wall of the roof	HVAC system in almost every room
Adaptive features	Balconies with wooden screens (*Mashrabiah*) to cool and filter the air, to provide additional shade for the windows and give privacy.	Large windows all around the house and usually unprotected from the hot sun a part from indoor screens that does not protect the house
Structure	Built with the traditional system which is a skeleton structure system consisting of bearing (columns, walls, and beams) and non-bearing elements (shutters, windows, doors, partitions and vents)	The structure varies depending on the design but normally heavy construction material is surrounded by a large solid exterior wall.
Materials	This system used local available materials such as coral stone, coral slab from the sea, palm beams, palm leaves, mud, and mortar	Building materials used are mainly reinforced concrete, cement, and hollow blocks covered by plaster, marble or stone.

Later, and as mentioned previously, the CH2M company was involved in building houses in both Dammam and Alkhobar city. In this context, the lack of knowledge of the local culture among the foreign companies which were involved in the development of the country (Konash, 1980, cited in Al-Naim, 2008) and the lack of cooperation between architects, both Saudi and non-Saudi (Al-Naim, 2008) along with the desire of locals to emphasise and reflect their wealth and prosperity, can be intimated as the causes of most of the key contemporary issues (Abu-Ghazzeh, 1997; Al-naim, 1998; Eben Saleh, 1998; Al-Naim and Mahmud, 2007). As a consequence, many buildings have been built to be architecturally western in style and concept, culturally alienating and climatically unsuitable (Roaf, 1990). Hence, the architectural situation has seen a significant transformation, which has led to the abuse of the local built environment and negation and elimination of many of its quality aspects, and has also fractured quite a lot of social values and exhausted much of its cultural wealth (Eben Saleh, 1998b; Eben Saleh, 2002) (Figure 2.5).

Figure 2.5 on the left, An example of an air-conditioning unit attached outside a traditional building during the eighties, which has abandoned the old traditional methods of cooling (Source: Talib, 1984) on the right, traditional neighbourhoods as they look in the present after the reconstruction of the dwellings by modern materials with the installation of mechanical cooling. (Source: the author).

2.2.4 *The Eastern Region climate zone*

The climatic characteristic of the Eastern Region is categorised as a composite climate (maritime inland desert climate). This location zone extends along the Arabian Gulf coast and inward in the direction of the desert for around 30 km (Figure 2.6). This composite climate presents a greater challenge for dwellers living in the built environment, since conditions fluctuate between hot dry, hot-humid, and maritime desert conditions in various locations (Talib, 1984). Dammam, for instance, is among the few areas in the world where temperatures during the harsh summer reach above 50°C (Table 2.2), with a range of high and low humidity, while, during the pleasant months of winter, the temperature drops to 6°C with high humidity (PME, 2010).

Table 2.2 the average maximum temperature recorded from January 2001 to December 2010 and the average of the maximum relative humidity over the same period. (Data Source: PME, 2010).

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
T max	31.3	36	40	45.3	48	50.3	50	49	46.4	46	39	32
RH max	90.3	92.5	88.5	84	76.5	73.8	79.8	82.7	88.8	93.8	89.5	90.8

According to the Presidency of Meteorology and Environment (PME) report (2010), Dammam has a high temperature range of 38°C to 50°C during May to October, cooling off towards November (24°C to 29°C during November to April), and an average temperature of 22°C during the pleasant months of December, January and February. The highest minimum recorded was 30°C during May to October, and the lowest average was 10°C during December to February. On the other hand, relative humidity throughout the year is above 30%. The records show that humidity during hot periods fluctuates between about 80% and 30%, with highs of about 60% to 95% during the rainfall season which is November to April. Thus, the challenges of high temperatures, humidity and glare for most of the year make conditions severe. It is also common for these characteristics to extend for more than half of the year (Figure 2.7).

Figure 2.6 Saudi Arabian climatic zone (legend source: Talib, 1984)

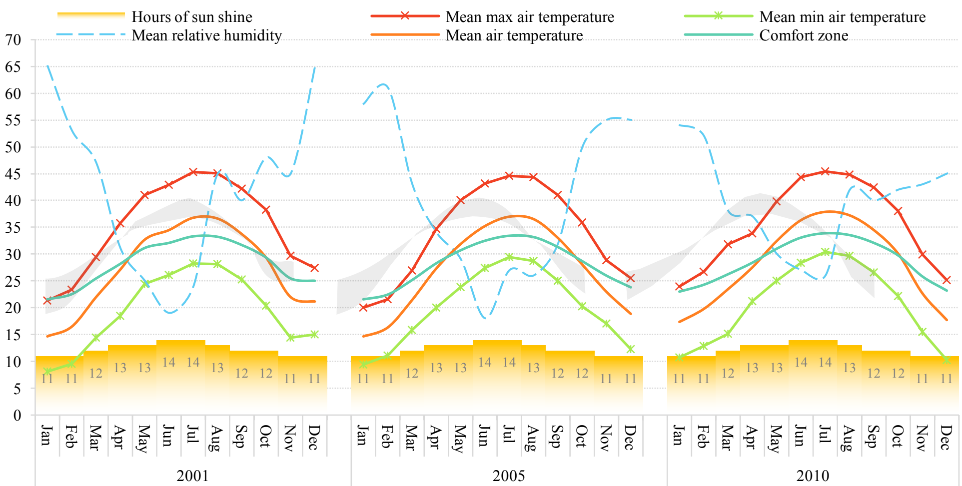


Figure 2.7 Dammam's Nicol graph for 2001, 2005 and 2010 represents the regularly mean relative humidity and mean air temperature across three years (Data source: PME, 2010).

Furthermore, an unusual climatic phenomenon has been monitored over recent years, represented by the continuity of a dusty atmosphere most of the year rather than just in a specific season (Figure 2.8). This has indeed complicated the conditions for people with regard to comfort in such an environment, which requires an extensive use of air-conditioning systems to provide a comfortable indoor environment, as well as a regularly repeated maintenance to clean the dust away from the mechanical systems.

City	T_{max}	T_{min}	RH	condition	City	T_{max}	T_{min}	RH	condition
Makkah	44	29	45		Tabouk	38	12	40	
Medina	45	30	25		Baha	35	20	65	
Riyadh	46	29	30		Arar	41	25	35	
Dammam	**48**	**30**	**85**		Sukaka	39	24	35	
Jeddah	39	25	80		Gizan	37	30	85	

Figure 2.8 Meteorological data for Dammam city on the 17th of June 2010. Which shows how harsh the climatic conditions are (high temperature, high humidity and dusty conditions in one day), (Source: PME, 2010).

2.2.5 *The expansion of energy consumption*

The statistics from the Ministry of Economy and Planning (2010) show that electric power consumption increased at an average growth rate of 3.2 %, in the period 2000 to 2012 (Table 2.3), and the residential sector in particular accounted for approximately 53% of the total energy consumption, which exceeded 8100 kWh per capita. Based on the population growth forecasts, the total consumption of residential subscribers risen from 3.6 million subscribers in 2000 to 6.7 million subscribers in 2012, which would require a significant amount of energy production. However, the up-to-date total energy consumption is not available yet.

Table 2.3 a comparison of the key indicators of the electricity sector between 2000 and 2012, (AGR: Annual growth rate), (Data source: MOWE, 2012)

	2000	2012	AGR (%)
Residential subscribers (million)	3.6	6.7	5.3
Average annual consumption (kWh per capita)	5600	8100	3.2
Maximum network load (MW)	22000	52000	7.6
Annual electrical production (GWh)	126000	272000	6.6

On the other hand, the price of energy services seems to be regarded acceptable in Saudi Arabia according to the website of the Electricity and Co-generation Regulatory Authority (ECRA) (ECRA, 2011). According to an Alriyadh newspaper interview, the governor of the ECRA, Mr. Alshehry, claimed that "the rate of consumption for electricity bills does not exceed 200 SAR (£33.3) for about 80% of the subscribers" (Alhaydar, 2011). However, in the online version of the newspaper in which this was published, around 92% of the comments registered criticised the interviewee by saying that "the governor was extremely idealistic and that does not reflect the reality at all" (ibid).

Table 2.4 The residential consumption tariff since 2001 along with the late 2015 tariff (SAR/kWh) *excluding the charge of meter readings, maintenance, bill preparation and the charge for service connection (Data Source: ECRA, 2011 and MOWE, 2015)

Monthly consumption (kWh)	1-2000	2001-4000	4001-5000	5001-6000	6001-7000	7001-8000	8001-9000	9001-10000	more
Old Tariff	0.05	0.10	0.13	0.13	0.15	0.20	0.22	0.24	0.26
2015 New tariff	0.05	0.10	0.20	0.20	0.30	0.30	0.30	0.30	0.30

Historically, low energy prices in Saudi Arabia encouraged users not to restrict their use of energy on the grounds of costs. The combination of a lack of awareness of the environmental impacts of energy consumption and the many social pressures to pursue an energy-intensive lifestyle mean that energy demand is extremely high in the region. However, in December 2015, the prices of domestic energy were increased overnight by 60%, for those high-end consumers who paid more than 300 SAR (£54.5) per month for their energy bills, so the cost of operating dwellings is soaring for many families (Figure 2.9).

2.2.6 *The cost of living in Saudi Arabia*

According to Albaaz (2008) in his social study, the subsistence level boundary for a Saudi citizen is 1660 SAR (£275) per month, whereas the poverty line is 1120 SAR (£185), without calculating the cost of housing and its related items. In fact, this is the latest data available, and since then, it is assumed that with the rise of the cost of living without a corresponding increase in income, the boundaries are even higher. It is believed that after the world economic crises in 2007, the cost of living has risen remarkably in the region. The share of housing related items, therefore, forms the largest portion of the spending. The steep increase in the cost of living after 2007, shown in Figure 2.10, indicates that households have been put under increasing financial strain, which means spending more, as shown, while the income level has remained the same. A significant proportion of the increase in the discrepancy between the cost of living and revenue has been accounted for the rise in the cost of electricity over the last decade (Albaaz, 2008).

To date, there has been agreement on how middle and low-income citizens have experienced many impediments to affordable houses, from the stage of purchasing a plot to the stage of ensuring they have the required amount of money to build their houses. What has worsened the situation for people even more is the decline in the number of housing units produced or funded by government agencies (MEP, 2000), in addition to the constant decline in mortgage support by the Real Estate Development Fund (REDF) mortgages, concurrently with the massive increase in population.

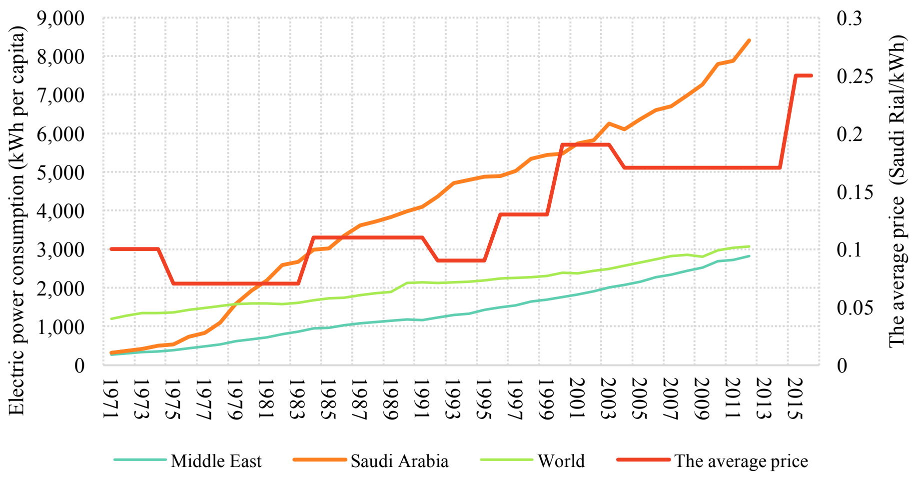


Figure 2.9 Electric power consumption (kWh/capita) in Saudi Arabia in the period 1971- 2010 compared with the consumption of the average of the world and Middle Eastern countries per capita (Data source: IEA, 2014), alongside the average electricity price among the residential tariff groups since 1971 to date (Data source: MOWE, 2015).

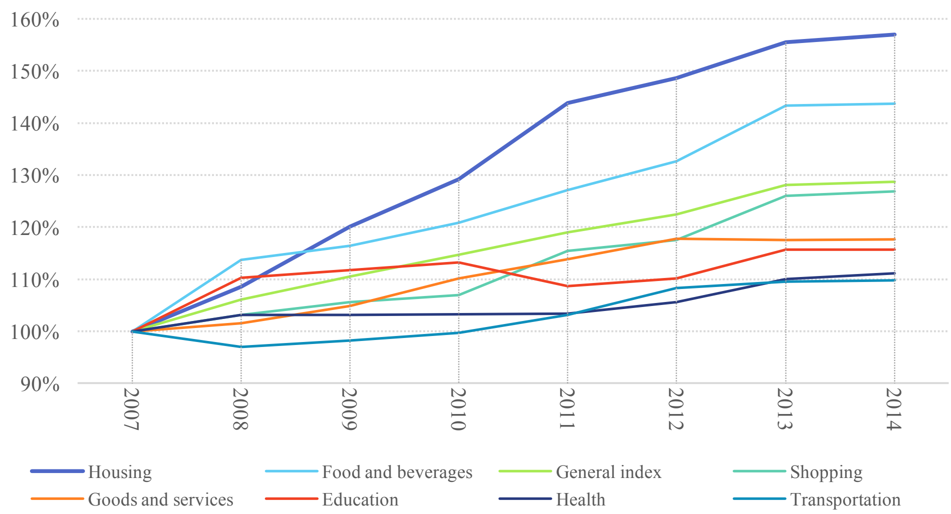


Figure 2.10 the cost of living increment including the housing operation cost (the cost of repair, rent, electricity, etc.) for Saudi citizens since the 2007 economic crisis. (Data source: IEA, 2014)

2.3 Thermal comfort

Almost everybody has a daily thermal routine. Within limits, it can be assumed how warm the bedroom will be when someone wakes up and how warm the kitchen is when having breakfast. People also may have an idea of what is expected in the car trip to work and at the office when they arrive. Although these expectations may vary from time to time and from season to season, it can give an overall idea of what thermal conditions to expect over a day or month, and people will generally have strategies for dealing with them. So why it is essential to know which temperatures are comfortable? And what is the point of thermal comfort science?

This section is divided into five parts. The first part looks at the history of thermal comfort. In the second part, definitions of thermal comfort will be reviewed. This is followed by a discussion of the importance of studying this topic and theories of thermal comfort are then discussed. Finally, specific design features are related to the thermal experience.

2.3.1 *The early beginning*

Since the beginning of human life on earth, the presence of liveable environments has ensured the sustained existence of humanity, which has also resulted in vital expansion for the human species. Thermal comfort is one of the basic necessities for the human body in a liveable environment. It is almost certain that the informal study of what thermal comfort requires predates all written history. Around 400 BC, however, Socrates wrote some thoughts on how to build a climatically suitable shelter to ensure thermal comfort. By the first century, Vitruvius also wrote his thoughts about the need to design buildings whilst bearing in mind the climate issue and seeking a healthy environment and comfort, even though it did not have very much impact on applied architecture (Auliciems and Szokolay, 2007). Archaeologists have noted certain evidence for the important presence of fire in early times, which is found almost universally in many remnants of early buildings (Stoops, 2000). Although fire was used ordinarily for cooking, it was fundamental for providing heat to attain some comfort as a minimum for an acceptable liveable thermal environment. This thermal solution has been found, frequently, throughout many civilisations as a design pattern. However, as most of these early patterns predate written language, there is no written evidence of the rationale for selecting particular design solutions.

The design pattern varies from one climate to another as well as differing culturally. For example, societies with cold climates developed various complex solutions to survive the severe weather. Those solutions mainly involved combining clothing, along with designing complex buildings for groups of people and animals, which frequently contained a fireplace or a stove to provide heat. Moreover, lots of these traditions perhaps developed religious relationships and patterns as the first fire worship rites were formed in some of the oldest folk traditions, which continue in many parts of the world. For cultures that had to cope with hot environments, on the other hand, where they had to cool their habitats, extraordinarily creative design answers have been revealed, with enhancements of either water evaporation or air ventilation or a combination of both (Heschong, 1997 p:15).

Moreover, some of these design patterns have augmented and enhanced the societal aspect. For example, public baths were very popular in ancient Rome as well as in Japan. The public baths of ancient Rome were a luxurious thermal place found only in rich aristocrats' houses, for the people who had enough money to afford the payment needed for transforming and heating the water. Then over a period of time, the idea of building public bathhouses was established, first for a trivial amount of entrance money, and then, within in a short time they became free (Hays, 1998). On the other hand, the hot baths were more of a social gathering for the Japanese; it became a part of the daily routine, and they perhaps exaggerated the occasion, claiming that whoever did not go there was either sick, angry or antisocial (Heschong, 1997 p:47). Although they provided a social place for meeting in both societies, for the Romans, they were, more importantly, a source of warmth, as opposed to other aspects. From the time of Socrates until the Industrial Revolution, there were not many influences over thermal comfort because of the limitation of practical concerns, as well as the limitations of tools and techniques.

By the late eighteenth century, heating technology improved dramatically. According to Heberden (1826, cited in Auliciems and Szokolay, 2007), by the early nineteenth century, it was acknowledged that it is not only the air temperature that matters, but the factor of humidity also plays a major role in thermal sensation (Bedford and Chrenko, 1974). The first systematic study of thermal comfort was reported in the United Kingdom by Haldane in 1905 (Auliciems and Szokolay, 2007 p:5). By the second decade of the last century, a primary study was carried out in the United States to find a comfort zone by means of the air temperature and the level of humidity. Since then, engineers have been very keen to explore comfort, and in the early twentieth century, mechanical cooling became possible; ever since, the topic of thermal comfort has been the subject of much research. Victor Olgyay (1963) reported vital work interpreting several researchers' results and was the first who introduced and established the issue of thermal comfort and the comfort zone on the bioclimatic chart and its relation to functional architecture.

2.3.2 *Definition of thermal comfort*

It is necessary here to clarify exactly what is meant by thermal comfort. Olgyay (1963, cited in Auliciems & Szokolay 2007) was apparently the first to simplify the notion of thermal comfort with the idea of the "comfort zone." He clarified the term as a state just below what a human being achieves in lessening the amount of desired energy consumption to adapt to the surrounding atmosphere. Although it seems that this is reasonably precise, the range of comfort in this definition varies between individuals.

The broad use of the term thermal comfort is sometimes equated with The American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE, 2004) as "that condition of mind which expresses satisfaction with the thermal environment". Perhaps this is a perceptual process and indicates psychological as well as physiological factors. However, ASHRAE's definition has not clarified what the "condition of mind" might be a consequence of- whether a state of knowledge, or process of perception, or cognition, or a common feeling or attitude, and it might vary from one person to another (Heijs, 1994).

Despite the ASHRAE definition of thermal comfort being more psychologically based and being subject to several criticisms, it is the most widely known definition and perhaps the most well-accepted definition by researchers. Moreover, according to the ASHRAE definition, thermal comfort is partially subjective because several objective properties related to the comfort of the environment that are difficult to measure. However, according to a definition provided by Benzinger (1979), thermal comfort is "a state in which there are no driving impulses to correct the environment by behaviour". For Hensen (1990), Benziger has defined an objective definition of thermal comfort.

Another recent clear and operational definition of thermal comfort has been presented by Givoni (1998), who states that it is "the range of climatic conditions considered comfortable and acceptable inside buildings." However, Givoni does not indicate any thermal discomfort sensation as it seems that there is a difference between thermal sensation and thermal comfort (Geldard, 1972).

2.3.3 *Thermal comfort scale*

Thermal sensation is basically an expression of the feeling of coldness or warmth. Parsons (1993), claims that the term 'sensation' cannot be defined in physiological or physical expressions. Therefore, it is rated using a seven-point numerical scale. Thus, how people define their feelings is a fundamental question. A simple possible method is to question the subject to specify his or her feeling in terms of warmth (ASHRAE scale), or being comfortable or uncomfortable (Bedford scale) (Figure 2.11).

The initial use of the ASHRAE scale was in America, while the origin of the Bedford scale is in England, from Bedford's comfort survey. It is obvious that there is not much difference between the two scales except for the insertion of comfort in Bedford's scale (Nicol 1993). Moreover, the two scales behave similarly in practice, and the findings obtained could be comparable, as many researchers have found (e.g., Brager et al., 1993; de Dear, 1986; and Nicol, 1994). In practice, however, the three central categories equivalent to the sensation scale could be considered to be the comfortable zone (Oseland, 1997). For instance, in Bedford's sensation scale "comfortable, comfortable cool, or comfortable warm" could be used as an indication to discover whether occupants are comfortable under such circumstances (McIntyre, 1980). Although achieving full satisfaction with comfort is very difficult, this clue might ease the task for architects and designers.

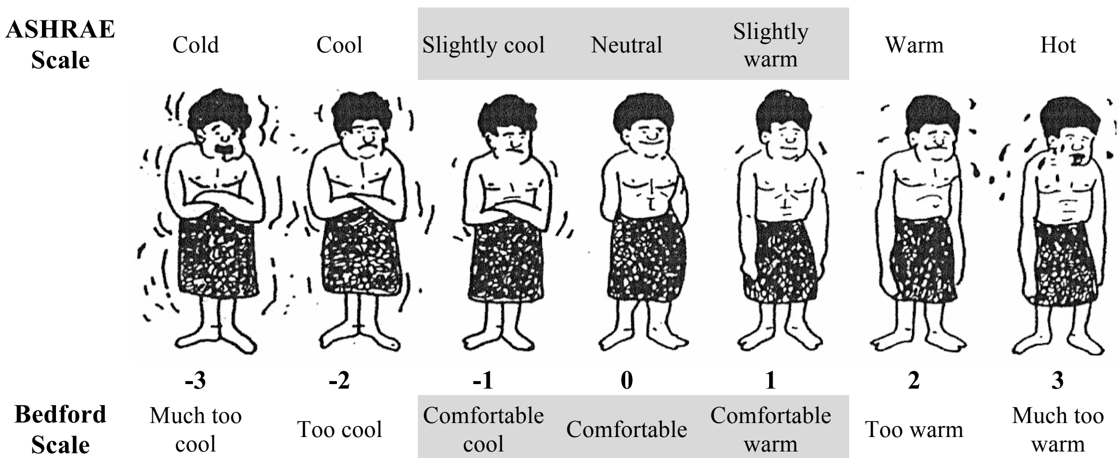


Figure 2.11 The seven-point numerical scale as demonstrated in the ASHRAE and Bedford scales, and the shaded points show comfort equivalents (Adapted from : Auliciems and Szokolay, 2007)

2.3.4 *The need to study thermal comfort*

Since the end of the nineteenth century, researchers have been interested in thermal comfort. Understanding what circumstances will create thermal comfort and an acceptable thermal atmosphere has been emphasised (Parsons, 1993). Nicol (1993) has specified three motivations in understanding the significance of thermal comfort. Firstly, it is to deliver an adequate condition for occupants. Secondly, is to monitor energy consumption. Finally, is to set and propose criteria for such thermal circumstances. In addition, Huntington et al. (1951, cited in Auliciems & Szokolay, 2007) claimed that each building element should be designed to react with the climate and provide comfortable conditions for occupants, because when the occupant is in his or her most comfortable state, they will generally be at the highest mood attitude; likewise, a person's mood will worsen during an uncomfortable time. Raw & Oseland (1994) listed six benefits from researching thermal comfort:

- The environment will be controlled by people.
- The internal air quality will be improved.
- More energy saving will be achieved.
- The harm from producing CO_2 in the environment will be reduced.
- The efficiency of the building's occupants will be enhanced.
- Improving or changing standards will be reasonably advanced by recommendations.

Finally, almost 95% of people spend the greatest part of their lives in artificial environments (Fanger, 1970); therefore, high quality indoor environments will benefit the health of the occupants.

2.3.5 *Features of the indoor environment*

As previously mentioned, any building must offer a healthy atmosphere in a proper environment. This environment must simultaneously provide an acceptable liveable environment in each aspect, to subsequently minimise discomfort.

In reality, discomfort can be described as a condition with a lack of comfort. So, buildings free from aspects of discomfort would enhance the health of their indoor environment, therefore this is the condition that should be achieved by each environmental aspect.

Historically, many subsequent buildings were cooled with ice placed in the air supply ducts but by 1918 the US heating, ventilating and air-conditioning (HVAC) industry had all built mechanical ventilation systems that incorporated humidity control to improve indoor comfort (Steadman, 2014). By this stage, US designers had identified humidity as a primary cause of summer discomfort and air-conditioning systems were increasingly designed not only to cool the air but also to manage its humidity. The designers decided, then, that 55% RH was the maximum level to strive for, which still as a standard for controlling humidity (ASHRAE, 2008). The consequence of this assumption was to push systems to use a two phase conditioning systems, first chilling down the air to remove humidity by condensation and then reheating it to further reduce its relative humidity. But the cost of this was significant energy inefficiency to get air to the required temperature. In addition, living in a high humidity environments could increase the concentrations of specific types of mould bacteria and/or high populations of dust mites inside homes which would directly affects people's health (Porteous et al., 2014)

However, a common symptom of the use of air-conditioning systems is the over-drying of indoor air that can typically be as low as 10%-35% Relative humidity, whereas it has been found that increasing humidity in such dry buildings to above 40% has no measurable influences on occupant health (Nordstrom, Norback, and Akselsson, 1994). Moreover, if the core concern is occupant comfort, the subsequent century of research has often contributed to the confusion about the actual role and impact of humidity at high temperatures (Humphreys, Nicol, and Roaf, 2015).

A wide range of 20th Century tropical comfort indices were developed based on laboratory experiments (McArdle et al, 1947) or the results of field studies. Webb (1959), Nicol, (1975), Sharma and Ali (1986) and others linking humidity, temperature, and air movement to comfort in a single 'comfort index'. In 1973, Nicol and Humphreys presented the results of field studies in the UK, India, Iraq and Singapore (Nicol, 1975) with results showing that average comfort vote changes little with the mean temperature experienced in previous study (Nicol and Humphreys, 1973). A number of meta-analyses of the role of humidity in comfort in tropical regions have been undertaken including that by de Dear et al (1991), Fountain et al. (1999), Nicol (2004) and Givoni et al (2006). They conclude, in line with the field studies on which they are based (i.e. Busch, 1992) that comfort can be experienced in hot and tropical regions even with humidities and temperatures, which are high when judged against Western standards.

- Thermal environment

The thermal environment can be controlled in two different ways: Firstly, which is most commonly used, by letting the temperature of the air behave primarily as an overruling influence, leading to comfortable conditions. The second way is by controlling not only the air temperature, but more than one feature of the thermal environment, although such methods have not been in extensive use so far (Croome and Swaid, 1993). One of the most advantageous strategies is thermodynamically cooling existing architectural spaces using the mass of the building itself as the thermal system rather than air (Moe, 2010)

The entire control of thermal comfort requires other aspects to be included to balance thermal comfort between the environment and its occupants. The environment's characteristics are, specifically, air temperature, radiant temperature, air velocity and the level of humidity, which must all be taken into account, in addition to the human factors, which include the clothing level and metabolic rate. These variables of thermal comfort may be easily measured, and then linked and compared with occupants' observations of the environment.

- Indoor air quality

Indoor air quality is relatively hard to measure because of several factors, which may or may not interact. Moreover, the air's chemical components in a particular place are different to another place, and these play a crucial role. Furthermore, the presence of organisms, such as dust mites, mould, bacteria and microbes also affect air quality.

Humans perceive air quality based on their ability to notice these air components. It is important, thus, to assess the existence of the various constituents using professional equipment, otherwise it is not very easy to obtain a comprehensive understanding of all the existent aspects. Fanger (1988) developed a concept called "Olf and the Decipol", quantifying the concentration of air pollution as perceived by humans. Porteous (2011) explained the "Olf and the Decipol" concept as "one Decipol is a contamination caused by one person (one Olf) ventilated by a fresh unpolluted air for one person" which helps to form a technique that allows occupants to perceive the indoor pollution level and air quality.

- Freshness

Freshness can be defined as a factor that depends on other casual factors for thermal comfort, including air movement, air temperature and humidity. However, as mentioned before, other air quality aspects like smell may affect the condition.

According to a definition provided by Croome (1996), he includes such principles of freshness as "cold, new, salubrious, cleanliness, preserved, and ventilated," contrasted with other opposite meanings like "stale or stuffy".

Bedford and Chrenko (1974) quoted Sir Leonard Hill concerning the connections between thermal comfort factors and freshness: "for air to feel fresh it must have such cooling and evaporative power as suffices to keep the head pleasantly cool and the skin free from sensible perspiration." He further clarifies how air temperature and air velocity are crucial to predict the perception of freshness of the subject's head in all seasons, bearing in mind the importance of delivering a stimulus to the subject's body, which will increase the impression of freshness by altering the air temperature and air movement.

- Light environment

Providing enough and the correct type of light to gain satisfaction with the indoor environment is crucial. However, although providing these qualities is not very easy, dividing the lighting environments into more areas, with a mixture of artificial and natural light to enhance the light level, will help.

Too much light could disturb the user. A high proportion of lighting through daylight or artificial light can cause glare in the indoor environment, which may minimise vision or give an inadequate appearance. Therefore, designing the lighting pattern carefully can perhaps prevent occupants from being affected by such issues.

- Acoustic environment

The acoustic environment is also vital in ensuring satisfaction with the indoor environment. It constitutes the changing noise level. Expecting or not expecting noises can play a role in people's opinion on noise.

It is fundamentally significant to adapt an environment by adding proper physical noise absorbers and barriers using various types of materials. In addition, Sharland (1990) claims that providing white noise in the background, such as a waterfall, rainforest or music, could conceal other unwanted sounds.

2.3.6 *The architectural design*

It is generally understood that the design layout and the furniture have a major influence. For example, locating furniture wrongly may cause medical problems, as well as complicating movement, and it could result in chaotic spaces. The number of people per m^2 also has an effect. The designer's duty is to ensure that it reflects people's needs and simplifies the occupants' daily tasks. Through this approach, certain health problems can also be avoided or minimised.

2.3.7 *Human perception*

The type of building and its environment, as well as the occupant's background, for example, will affect perception (Gibson, 1979). In general, a study of this aspect involves opinions about the environment. An example of occupant's sensations of how satisfactory a feature is, if they like a certain feature or not, helps to obtain an opinion of satisfaction or dissatisfaction with the environment using a holistic overview.

2.3.8 *Theories of thermal comfort*

As mentioned previously, various efforts have been made to forecast thermal comfort. Therefore, improving comfort models has interested many researches in many different areas. The fundamentals of theoretical work using thermal comfort models are based on thermal exchange theory as well as the mechanisms for supplying thermal balance. Physically, heat is transmitted from or maintained by the human body in order to reach thermal balance between the environment and the human body, which is called the thermal exchange theory. Gagge (1937, cited in Auliciems & Szokolay, 2007), Fanger (1970) and many others have implemented this model as the core for calculating the conditions necessary for a thermally comfortable environment.

Fanger (1970) explains the heat exchange theory by saying: "Since the purpose of the thermo-regulatory system of the body is to maintain an essentially constant internal body temperature, it can be assumed that for long exposures to a constant (moderate) thermal environment with a constant metabolic rate, a heat balance will exist for the human body i.e. the heat produced will equal heat dissipation and there will be no significant heat storage within the body."

A human characteristic is that when the body increases activity, it produces substantial heat, and through clothing insulation, the body maintains heat. McIntyre (1980) and Parsons (1993) developed a more complete understanding of the theory. McIntyre states that heat loss from the body occurs by convective heat transmission into the atmosphere, or through “moisture evaporation”, which is basically radiation to nearby surfaces. Parsons further clarifies two types of thermal index: “the direct indices” and “the rational indices”. The first type uses instruments to simulate the human response to the operative temperature, while the other one uses heat transfer equations, such as Fanger's model, and the effective temperature index. Nevertheless, a report by Humphreys (1994) declared that testing thermal sensation is strongly connected to the occupant’s predicted thermal perception, together with the indoor air temperature. Furthermore, Humphreys claims that research results show that air temperature is a very useful predictor of thermal sensation, along with other complex model predictors.

2.3.9 *Factors of comfort*

Auliciems and Szokolay (2007) classified the factors that affect thermal comfort into three groups: environmental factors (air temperature, air movement, humidity, and radiation); personal factors (metabolic rate and clothing), and contributing factors (food and drink, acclimatisation, body shape, subcutaneous fat, and also age and gender).

- **Environmental factors**

Air temperature is the most important environmental factor. It determines the convective heat dissipation from the skin. Air movement accelerates this process and also affects the evaporation of moisture from the skin, thereby increasing the evaporative heat loss. The humidity of the air also affects evaporative cooling. If the absolute humidity (moisture content of the air) is between 5 and 10 g/kg, it has only a little effect on thermal sensation, while a high humidity (around 12 g/kg and above) would restrict the evaporative heat loss. Radiation is the function of heat exchange between bodies at different temperatures. It depends on MRT, the mean radiant temperature, of surrounding surfaces to which the body is exposed. It is weighted by the solid angle subtended by each surface. These factors will be explained in details in section 3.5.

- **Personal factors**

Metabolism is the biological process of transforming foodstuffs. It generates energy for human activities. When work is performed, the metabolic rate increases in order to produce the energy needed for the work. The surplus of about 80% of total energy produced in the body will be in the form of heat dissipated into the environment. Sweat secretion increases in order to restore the thermal equilibrium. The metabolic rate depends on the activity level. At a given level of activity, it also depends on age and sex, and is proportionate to the weight and size of the body.

The other personal factor is the subject's clothing. Givoni (1969) notes that the clothing has a major influence on the heat exchange between the body and its surroundings. It forms a barrier to convective and radiative heat dissipation into the environment and also interferes with the evaporative sweating process. The '*clo*' value as a unit used to define the level of insulating cover over the whole body, with an average transmittance (U-value) of 6.45 W/m^2K that described mainly in the ASHRAE fundamentals handbook (2009). Moreover, clothing as an important role of the behavioural adaptations of individuals, that differ by cultures and climate, the clothing value vary as well (Humphreys et al., 2015). Al-Ajmi et al (2008) give the characteristics of traditional Arabian Gulf clothing (see Appendix III).

- **Contributing factors**

Contributing factors include food and drink, acclimatisation, body shape, subcutaneous fat, and age and gender. Food and drink affect the metabolic rate. Acclimatisation can be both the short-term adjustment (20-30 minutes) and long-term (beyond 6 months). The human body responds to its environment differently due to different limits of exposure. Thermal comfort limits vary depending on individuals. Body shape and subcutaneous fat are important, as heat dissipation depends on the body's surface-to-volume ratio. Therefore, a thin person would lose body heat into the environment better than a person with a larger body shape. The subcutaneous fat is a good insulator; thus, it causes the fatter person to prefer a lower temperature.

2.3.10 *Thermal comfort in homes*

The first step when approaching a new design should always be to try and understand the overall climate of the site and how much protection the house will need to provide against the harsh climate. A simple way of doing this is to apply the Nicol graph (Figure 2.7). The comfort curve is calculated using the equation:

$$T_c = 0.534\ (T_{mean}) + 11.9 \qquad (2.1)$$

which is the temperature at which the average person will be comfortable in most buildings (without heating or cooling) from that outdoor temperature.

- T_c is Comfort Temperature (°C)
- $T_{mean} = (T_{max} + T_{min}) / 2$), monthly mean indoor temperature
- T_{max} is monthly mean daily outdoor maximum temperature
- T_{min} is monthly mean daily outdoor minimum temperature
- T_{min} and T_{max} are usually available from Meteorological Office data

Although this equation applies only to summer conditions in free running buildings (not air-conditioned ones), it provides an overall awareness of the comfort conditions necessary for people to adapt themselves to the local climate.

A Nicol graph can be used to give a rough idea of the amount of heating or cooling required in each month for the building. In a good passive high mass building, the indoor air will tend to revert to a temperature half way between the mean outdoor and mean indoor temperatures. So a line can be drawn half way between the two to indicate the free-running indoor air temperature. If this is below the T_c, then the building will need heating up to make the occupants warm and vice versa.

If a large amount of heat is required, it can be partly supplied by passive systems. If a great deal of cooling is required, it may be possible to gain it through ventilation. Convective cooling is effective up to average skin temperature (around 32 - 34°C), and even above that temperature range it will help with evaporative cooling of the skin. A fan can provide cooling equivalent to a 2 - 4°C drop in temperature in hot conditions, with relatively little energy.

Thus, with a simple graph it is possible to tell how much we want to welcome in the external climate at different times of the year, or how much we want to keep it out. The graph also gives an idea of how much extra energy is needed from supplementary heating or cooling systems to reach the T_c. This is an effective way of looking at the passive potential of a building in a particular climate and using this knowledge to choose an appropriate building form to optimise this passive potential.

It is also worth noting that a well-designed passive building should be able to provide up to 3°C free cooling by using ventilation at the coolest time of day. However, it is not only the design that has opportunities to provide comfort, it is the adaptation of the occupants as well, possibly adapting themselves to shift between discomfort and relative comfort. Therefore, there are three levels of opportunities, design features, adaptable building features and alterations in the occupants' behaviour or attitudes.

Roaf et al. (2013) describe these opportunities and arrange them by significance, as the design opportunities are the basis of the provision of comfort and then other opportunities are supportive and complementary to the level of pleasure. The dwelling's design opportunities include; the orientation of the dwelling, dwelling form, openings and solar access, the height of floors and building, ventilation strategies, solar shading, insulation and construction materials. The opportunities for adaptation involve, opening windows and infiltration, furnishing, cooling systems, landscaping, shades, curtains and blinds, and occupant lifestyle. Finally, the third level of opportunities includes sensations and perception, colour and lights, view and links with nature, decoration style, and the provision of ambient noise.

2.4 Summary

This chapter has presented the two topics which provide the context for the study, the evolution in building types in Saudi Arabia and a literature review of the subject of thermal comfort. The section on the Saudi context firstly presented the geopolitical background for the study, secondly, it traced the evolution of the designs of the contemporary dwellings, concentrating on the period after the start of oil exploration in the region and thirdly, it provided an overview of the complex climate issues existing in the region of Dammam. Energy consumption in the residential sector of the region was then discussed, particularly concerning future demand arising from the incremental increases occurring in the population. Finally, the standards of living in Saudi Arabia were examined and the impacts of the increase of electricity consumption discussed in relation to related affects that may occur in the ability of individuals to live affordably in comfort.

The second part of this chapter provided a background to subsequent discussion of thermal comfort in the following chapters. Definitions of thermal comfort and its scales and significance were given and the indoor environmental contributors to the thermal conditions were explored. After discussing this theoretical overview of thermal comfort, the factors affecting the thermal experience of individuals, including the environmental factors, personal factors and contributing factors were briefly discussed. Finally, the three levels of opportunities to deliver thermal comfort in homes were classified, including the design characteristics, adaptive qualities and the adaptations in the sensation levels of occupants.

CHAPTER THREE: RESEARCH METHODOLOGY

"Scientific method, although in its more defined form, it may seem complicated, is in essence remarkably simple. It consists of observing such facts as will enable an observer to discover general laws governing facts of the kind in question."

Bertrand Russell

3.1 Introduction

This research considers the environment within Dammam homes, an environment that cannot be easily classified, because of its phenomenal complexity. The closer a researcher can get to the core of well-defined problems relating to such environments, the better will be the resulting understanding of complexities of the perception and performance of the spatial context, the behaviours of its occupants and other properties and qualities of a particular environment.

In the first section of this chapter the methodology used in this study and the variables measured in it are described. and explained. Following this, the method and tools employed for data collection, including measurements of individual parameters, and the scales and design of questionnaires are presented. Finally, the scope and limitation of this type of research is explained and justified.

3.2 Overview of research methodology

Fundamentally, the integration between social and environmental science in this research involves a constant interplay between observation and explanation, the collection of further facts to test the explanation, a refinement of the explanation, and so on (Vaus, 2002). The crucial factor influencing which method to select is the nature and quality of the research, i.e. whether it is observational, experimental, or some other form. Each approach has different types of design and tools to facilitate and fulfil its need to determine a rational and logical technique to approach and explore the problems under investigation. These designs and tools also assist in achieving the research objectives.

The fundamental principle with which to judge the success of any approach for these types of studies are the degree of appropriateness and trustworthiness of the data collected and analysed through the particular approach. This data probably will form the basis of a whole set of explanations, interpretations and predictions for the research problem. Moreover, fundamental decisions could be made on that foundation, so the right methodology is vital for effective results.

In order for the current study to conduct a thoughtful investigation and to have a clear understanding of the characteristics and habits of home users, the notion of employing more than one method, for accurate and 'mutually supportive' data collection, appears to be more reliable (Ragin and Becker, 1992; Stake, 1995; Kitchenham, 2010; Yin, 2014). As Patton (1987:60) points out that as any single collected data strategy has its own strengths and weaknesses, the researcher can overcome this by using more than one approach, thus combining between strategies and avoiding some of the weaknesses will elevate the outcome. In the same context, Kitchenham (2010:563) sums up this approach as it *"…allows opportunities for the meaningful questions to be posed, measured, analysed, and interpreted. Because both inductive and deductive reasoning are applied in mixed method research, the results are far more robust, especially in case study research that involves rich empirical data gathered through varied data collection techniques. In short, mixed method research is so powerful because it allows the 'gaps' in qualitative research methodologies to be filled or overlapped by quantitative methodologies and techniques and vice versa".*

Therefore, any individual technique may respond to part of the research objectives, but may not be enough to cover all the major dimensions. Thus, the integration of different methods would be more fruitful.

3.3 Method adopted for the research

In accordance with the research aim and questions, the overall methodology combines published works, drawings of the studied dwellings and mixed-methods data collection regarding user's behaviour and the home's physical environment (Figure 3.1). While English language publications and the internet are the primary sources, specific literature related to the Saudi context has been collected from Saudi universities and public agencies. The literature review of thermal comfort, through which the theoretical background and the concept of thermal comfort have emerged, has been comprehensively covered.

3.3.1 *Case study and fieldwork method*

The nature and type of questions that this research aims to answer suggest a 'case study' as the most appropriate research method (Hamel et al., 1993; Stake, 1995; Yin, 2014), a place where researchers into house design and control can observe and record real signs of people's comfort and satisfaction.

Generally, the case study approach may depend on qualitative or quantitative methodologies or both (Stake, 1995; Yin, 2014). It is adopted to provide interpretations regarding the researched subject (Stake, 1995; Yin, 2014). Despite the fact that Yin (2014) argues that there is a slight difference between case study and fieldwork methods, this research regards the concept of fieldwork as a data collection technique that is part of the case study method, Yin himself defines the required procedure as "*an empirical inquiry that investigates a contemporary phenomenon within its real-life context*" (Yin, 2014:13). Thus, the best way to deal with the research matter at hand was to carry out a field study.

With regard to the importance of the field study Stebbins and Shaffir (1991:18) maintain that: "*Unlike controlled studies, such as experiments, field studies avoid pre judgment of the nature of the problem and hence the use of rigid data-gathering devices and hypotheses…Rather, their mission is typically the discovery of new propositions that must be tested more rigorously in subsequent research specially designed for this purpose".*

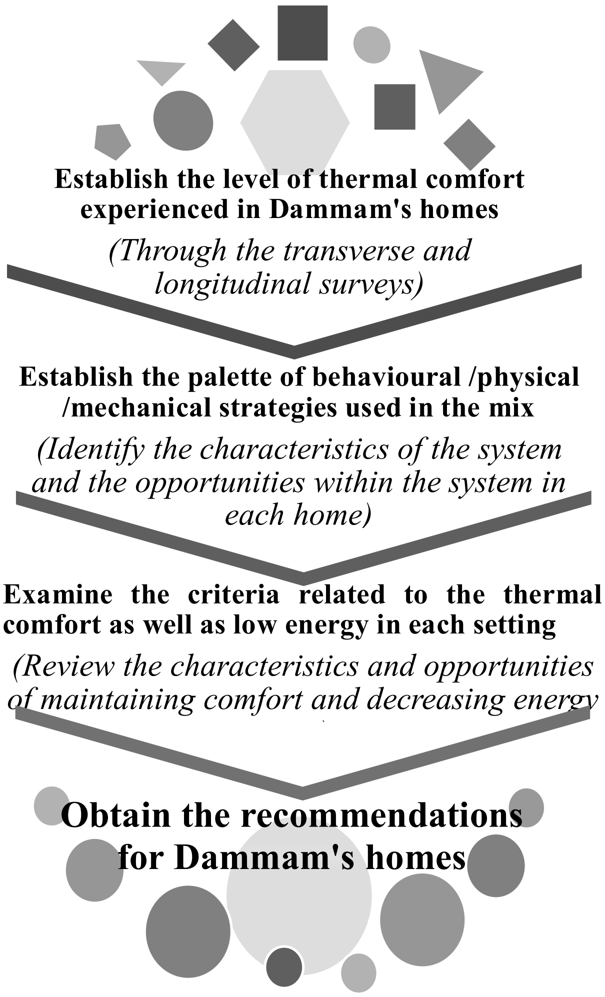


Figure 3.1: The research criteria to be fulfilled to obtain the recommendations

3.3.2 *Thermal comfort survey*

There are two main methods to determine thermal comfort, namely, through climate chamber experiments or through field study experimentation. Climate chamber experiments can be conducted in laboratory settings, whereas field studies can be undertaken anywhere as long as you have the appropriate tools. The methodology used for this research is thermal comfort observations through a field study. The advantage of this choice is that it is in-situ experimentation, so the findings can be useful to be applied to other similar thermal environments that have the same social, cultural, and economic conditions. The environmental and individual criteria cannot be determined precisely, so the results are applicable to the normal environments experienced by the occupants through the period of the study.

There are three levels of field surveys: level one consists of simple measurements of temperature in occupied space without individual responses; level two involves measuring the condition of the thermal environment and the subjective response to it; and finally, level three surveys all the factors, needed to calculate the heat exchange between individuals and the occupied environment, together with their subjective responses (Nicol, 1993). In this research it was decided to use levels two for the field study.

Two fundamental approaches will also be used in the field study, the transverse and the longitudinal approaches. The longitudinal method is to collect data from relatively few respondents and to repeat the surveys over a period of time, whereas the transverse approach involves collecting data from a large number of respondents, with only one assessment at a particular time and in a particular space. It is possible, from the longitudinal survey to examine the reliability of individual responses and see the progression of their adaptation to conditions, while the transverse survey indicates the degree of difference among individuals, which delivers a valuable perspective for a whole population, so these two types of study are complementary to each other (Humphreys, 1976).

There are a number of subjective scales, which have been used in the assessment of thermal comfort, i.e. the Bedford and ASHRAE scales. The form and method of the implementation of the scales is crucial, in which subjects choose points on a scale between cold to hot, as in the seven point ASHRAE scale. The scales representing the participants' responses give, or assess their physical and psychological conditions (For more details see section 2.3.3).

The researcher designed smartphone software called "ComfApp" (as shown in Figure 3.2) for the thermal comfort longitudinal survey to be operable on all smartphone platforms, making it easier, and more enjoyable, for subjects to respond during the day/night time and in any situation. The app assigned for each case as a unique serial number associated with the instruments installed on individual home. The survey included six questions and also requested personal information from subjects. The questions involved; thermal sensation, using a seven- point ASHRAE scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot); preference scale (much cooler, a bit cooler, no change, a bit warmer, much warmer); humidity sensation, using four-point scale (very humid, humid, slightly humid, not humid); metabolic rate, clothing and the individual's adaptations at a specific time and in an occupied room. The thermal scale and other sections of the questionnaire were translated into Arabic. As the culture and religion is taken into account, the values of clothing insulation were mainly derived from Al-ajmi et al. (2008) as well as from clothing values used by Nicol et al. (2012: pp.18). The metabolic rates given in ISO 7730 (cited in Nicol et al., 2012: pp.104) were used in this study. (see section 2.3.9, and also Appendix III). Furthermore, in order to understand the whole situation, demographical data about the subjects were collected through parallel questionnaires, as well questions related to the design of the houses being observed.

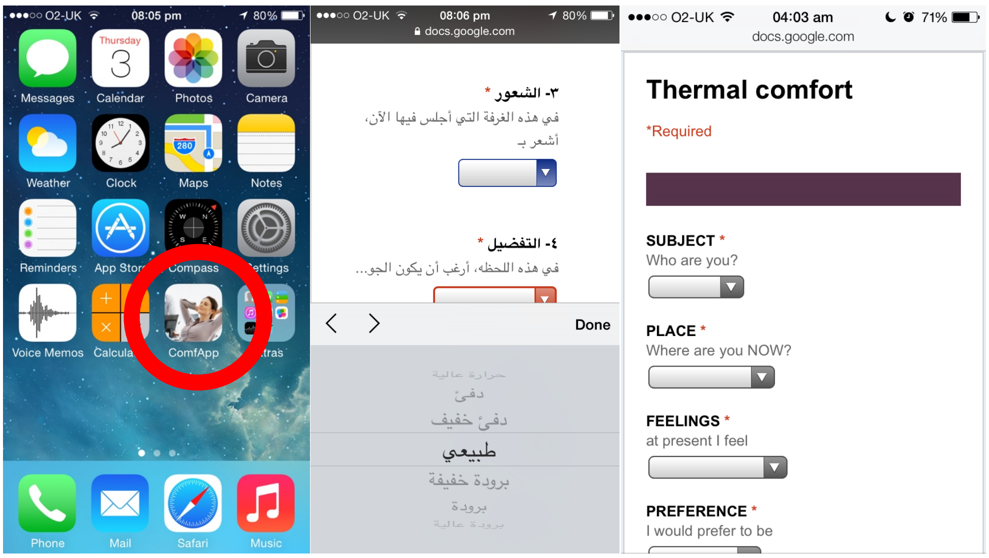


Figure 3.2: The interface of "ComfApp", the smartphone application that logs the occupant's actual mean choice.

3.3.3 *Questionnaire*

Questionnaires as a quantitative data collection method can be distributed in paper form or sent by e-mail or post or can be filled in during a face-to-face interview be (Neuman, 2013). In the current research, and after the experience from a pilot study, the use of questionnaire interviews is preferred, in order to ensure gathering a sufficient number of questionnaires, due to people's unwillingness to volunteer such information unless they are in a face-to-face situation. as well as to make it easier to ask questions and discuss the responses (Neuman, 2013) and to deal with potential cases of illiteracy.

According to Zeisel (2006), the purpose of using questionnaires is to determine and establish the similarities between people matching their answers to the same question. The role of using 'precise questions', therefore, is to provide a set of reliable measures (Neuman, 2013). The questionnaires, primarily, will be distributed and completed within each subject involved in each case study and gathered with transverse comfort survey simultaneously.

There are two types of questionnaires those consisting of; open-ended questions (unstructured, free response) and closed-ended questions (structured, fixed response). The critical aspect is not which form is best, but in what circumstances it is most appropriate, and for what purposes and what are the practical limitations. Although open-ended questionnaires are considered time-consuming and closed-ended questions seem preferable because they save time and effort, the participants of this latter type, may neglect or overlook crucial beliefs and feelings (ibid). Therefore, since both types have certain advantages and disadvantages, this study suggests a questionnaire consisting of mixed-style questions.

It is essential to take into consideration when designing questionnaires, to create a specific and direct question in a clear language and avoid embarrassing, hypothetical and personal questions (Sinclair, 1990). Moreover, Parsons (1994) points out that the fundamental psychological and principles phenomena differ between all nationalities because of the language and culture, so it is necessary to avoid cultural threads that may cause dissatisfaction with the subjects in return. He also points out that the selection of subjective scales will depend upon the population under investigation and an initial investigation may be necessary to identify meaningful parameters. Moreover, Parsons described the methodology of applying questionnaires, as that subjects to be asked to tick the answer that represents their current feelings (ibid).

ISO 10551 (2001) presents the principles and methodology for the construction and use of scales for assessing the environment. Scales are in fact divided into two types; the first one is personal, and the second is environmental. The layout of the questionnaire, which has been designed and used for this research project was based on the above considerations explained above and the ISO methodology.

It is also based on other questionnaires by some researchers who are professionals in this field and others (e.g. Parsons, 1993; Nicol et al., 1994 and Humphreys et al., 2015). In addition to that, types of questions related to social interactions, personal influences, people's general feelings and personal wellbeing issues have been taken from Raw (1995) in order to make this research survey valid for the city of Dammam.

Subjects were asked to complete a questionnaire at the same time as the environmental variables were being recorded. Details of clothing and activities were noted for each subject. For the purpose of this research project, social interactions of the residents and their personal information and occupants' thermal sensation data have been included in the questionnaire. These data would include the age and gender of the subjects and his/her family; how many hours/day are spent inside the building including sleeping time and what time of the year they operate/shut off the AC. The subjective study involved collecting data using questionnaires, which were tested in a pilot study before starting the field work. For more details, see section 4.2 and Appendix I. The questionnaire is based on the following four sections:

Section A: Background and personal information, which elicited the demographic data about the subjects and their families, and other general information, such as social interaction within a neighbourhood.

Section B: General information about the house, which involved data about the construction of the house, and other factors, such as the outward appearance, the design and the thermal environment in general in the house. Also questions were asked related to the occupants' behaviour inside their houses, such as the number of hours per day spent inside the house and the use of mechanical ventilation and their preferred room etc.

Section C: This section is divided into two parts: first, the occupant's perceptions of the environmental conditions in bedrooms and living rooms, taking into account such aspects as noise level, natural and electric lighting, natural and mechanical ventilation; secondly, the occupant's thermal satisfaction in the house in general, bearing in mind the level of such characteristics as dryness, stickiness and draughtiness.

Section D: Thermal survey, which measures the thermal comfort indices at the moment of participating in the questionnaire.

Section E: People's opinion and personal wellbeing, to discover issues such as peoples' attitudes towards and thoughts on clothing, or whether there are, for example, factors that influence their choice to open a window rather than the use of a fan or AC. This section is comprised of open-ended questions.

At the end of each section 'any comments' were noted: for the purpose of the present work, the questionnaire was modified to include any notes or comments that might help the researcher to understand more about the environment and people's social life. This provided information, which, it was anticipated, would help to explain any sociological reasons for people's responses to their environment (based, for example, on their culture and background).

The questionnaire has been translated into the Arabic language based on the criteria set up by Humphreys et al. (2015). The translation was sent then to an English/Arabic translation centre for more accuracy, then the translated words used in the scales were also tested in a pilot study before distribution among the residents in the city Dammam, Saudi Arabia. The reasons for the pilot study or testing questionnaires are:

a. To test peoples' comprehension of each question;
b. To revise and simplify the wordings of questions in accordance with the feedback, to avoid ambiguity; and
c. To test the validity of the questions, which may contribute to research objectives.

After testing the questionnaire, a reason behind the modification to some questions was the finding that section E was very neglected. Ignoring this section was due to people's unwillingness to participate in writing for any length of time. Therefore, the researcher transformed this specific part into a dialogue/semi structured informal interview to understand the behavioural value and attribute behind the occupant choices as well as to build up awareness about the subject of thermal comfort in people minds.

3.4 The selection of the case studies

Case studies, for the purpose of this research, aim for more realistic descriptions, which can be integrated with the results from the surveys. They have been employed to investigate in further detail a limited number of houses where they can be used as explicit and illustrative examples from the wider sample. Moreover, and if appropriate, the researcher may have a chance to perform some site measurements, and draw up plans and sections and take photos, for more realistic descriptions that can be integrated with the results from the survey.

This study aims to investigate occupants' thermal comfort in their homes; however, organizing an extensive study in private homes can be difficult (Cena, 1994), due to the natural desire of people not to have their affairs interfered with. This issue is very critical, in countries with unique cultures, special customs, and with distinctive norms and values, such as those directed by religion, as in Saudi Arabia.

However, the relationship between the occupants and their environments is very crucial, so if the occupied space is "atypical or of unusual design" that may influence the field result in terms of validity and reliability (Nicol, 1993). This study was looking for typical contemporary dwellings in the city of Dammam. The choice of the dwellings to be used for the survey was based on the following criteria:

1. Located in Dammam, Alkhobar, and Dhahran, the main urban developments in the Dammam region.
2. Recently built houses, regarded as contemporary houses (not more than 30 years old).
3. Mixed mode air conditioned and naturally ventilated homes.
4. Typical in terms of design and material as far as possible.

Although the selection process of the case studies was based on these criteria, the availability and accessibility of the property limited the selection decision. This criterion was a crucial factor in the determination and selection of the cases. For privacy and cultural reasons, it was very difficult to find available places to take measurements without disturbing the family, and special arrangements had to be made in order to secure these units for investigation. Therefore, and because of this, the difficulty of finding a mutually compatible time for all families with regular coordination was an enormous limitation to gathering information in a such limited time.

This discussion will be continued later with a detailed description of these cases and will be given in the following chapter.

3.5 Field measurements

According to Humphreys et al. (2015) the first priority for researchers who are anticipating conducting a field survey is that they should have a clear idea of what to measure, and how to measure it. A field measurement is a form of observational instrument which represents the most basic and most direct method of obtaining data. This technique is used regularly in behavioural studies where the aim is to examine a specific pattern for performance and is usually conducted in the natural setting associated with the issues that are under investigation. In fact, conducting field measurements in real life is not an easy task to accomplish, especially when people are engaged with jobs, children and other life activities.

Measurements in the current study are of environmental or individual parameters. The former will be measured by tools provided by the researcher, while the others will be measured through the survey. The main environmental parameters are:

- **Air temperature**

According to Auliciems and Szokolay (2007) air temperature is the most important environmental aspect in field measurements. Humphreys (1976) notes that readings of air temperatures that are measured alone in a field survey will have been influenced, to some extent, by the mean radiant temperatures of the nearby surfaces. In fact, several researchers used only air temperature in their comfort studies, due to the high correlation between air temperatures and other form of measurements. Nicol and his team (1994), nevertheless, in their Pakistan field survey indicated that globe temperature and air temperature were quite similar. Therefore, the current study used air temperature as a principal physical variable in the longitudinal survey, alongside the globe temperature and mean radiant temperature in the transverse survey.

- **Relative humidity**

Humidity is a measure of the amount of water vapour in a sample of air. The most commonly used measure to describe humidity is relative humidity (RH%). In fact, there are other parallel measurements to quantify humidity like dew point (°C), water vapour pressure (pa), and absolute humidity (g/km^3) (Humphreys et al., 2015). These variables measure humidity, either directly (water vapour pressure – the pressure exerted by the water vapour in the sample, or absolute humidity - weight of the water vapour in a particular volume of the air) or through the interrelation between water vapour and temperature (dew point the temperature at which the water vapour condenses into liquid water, or RH, the water vapour pressure as a proportion of saturated water vapour at the temperature of the sample). All these thermodynamic parameters/humidity values were calculated manually using different equations then illustrated in the psychrometric chart of moist air at a constant pressure often equated to a sea level altitude. The measurements take a longer time to calculate, but with the psychrometric chart, which was pioneered by Willis Carrier in 1904, these values can be found within seconds (Gatley, 2004).

Hensen (1990) concluded that the impact of humidity on thermal sensation is perhaps expected as a slight effect. However, when temperatures are inside or near the comfort zone, variations in relative humidity from 20% to 60% do not have any impact. In fact, it can be crucial when environments become warmer (Gonzalez and Gagge, 1973). de Dear et al. (1989) found that occupants feel cooler immediately when relative humidity decreases, and warmer immediately when it increases.

In the present study RH was the measured variable and, initially, the results were analysed in terms of RH. However, absolute humidity was also calculated and then the data was re-analysed using this measure, for two reasons: absolute humidity is not directly affected by temperature (unlike relative humidity) but is a measure of the amount of water in the air; the amount of sweat able to be evaporated off the skin at higher temperatures (Givoni and Belding, 1962) is more directly related to absolute than to relative humidity (which is dependent on the air temperature).

Absolute humidity is defined as the mass of water vapour in a certain volume of air, which is commonly written as [g/m^3] (VAISALA, 2013) So, using the formula for absolute humidity to determine its value, if ideal gas behaviour is assumed, the absolute humidity can be calculated using;

$$A = C \times \frac{P_w}{T} \ (g/m^3) \tag{3.1}$$

where, C = constant 2.16679 gK/J, P_w = vapour pressure in Pa, T = temperature in K. Vapour pressure (P_w) is calculated by dew-point temperature, which has been calculated by air temperature and relative humidity.

- **Air Velocity**

In the mixed-mode ventilation spaces, especially if these are in a hot climate, air movement might have a slight influence on the thermal comfort of subjects. In the present study, an airflow meter, included in Kestrel 4400, measured air velocity. However, the amount of air velocity is only reported with the transverse technique, due to the limitation of the instruments.

The physical measurements taken included air temperature, and relative humidity and air velocity measured using data loggers, as described in the sections below detailing the different instruments.

3.6 Instrumentation

For the field measurement, two types of instruments, including Kestrel 4400 Heat Stress Tracker and KG100 USB Data loggers were used. All the instruments were portable and battery powered. The Kestrel 4400 Heat Stress Tracker was provided by the researcher due to the limitation of the school's budget, whereas 26 new KG100 USB Data Loggers were financed by the School of the Built Environment at Heriot Watt University. Therefore, the KG100 Data Loggers were ordered online then delivered to Dammam, Saudi Arabia, in order to carry out the experiments during the summer of 2013.

3.6.1 *Kestrel 4400 Heat Stress Tracker*

Kestrel-4400 Heat Stress Tracker is compact; battery powered, portable, waterproof and also has a large memory size for data logging. Furthermore, it can also log several parameters simultaneously, such as air temperature, globe temperature, relative humidity, mean radiant temperature, air velocity, wet bulb, altitude, and more than fifteen other factors. It is ideal for applications in indoor and outdoor environments. It can record temperatures ranging from -29°C to +70 °C and humidity ranging from 0 to 100%, with a memory of 2300 readings for each factor. It is able to sample the data at intervals from 2 seconds to 12 hours, with minimum, maximum, average and actual readings. Furthermore, it has a high resolution of 0.1°C and provides better accuracy compared to similar data loggers. When logging the external recording, it was placed in the shade area to reduce the effect of sunlight on the device. Figure 3.3 (left side) shows the equipment assembled on a camera tripod at a height of 1 metre.

3.6.2 *Kg100 USB data logger*

The KG100 USB logger is a small, lightweight, battery powered device with a LCD interface. It is ideal for indoor environment applications and is designed for recording temperature and relative humidity. It can record temperature ranges from -40°C to +60 °C with an accuracy of ±1.0°C between 0 - 50°C. The humidity measurement ranges from 10% to 99% and an accuracy of ± 4% up to 20%. KG100 can log up to 16320 readings with the ability to record the data at intervals from 1 min to 4 hours, with minimum, maximum, average and actual readings. Figure 3.4 (left side) shows the USB data logger fitted in the living room of one of the cases during the field survey.

3.6.3 *Instruments calibration*

The instruments are not certified because no absolute readings were needed. The instruments were tested against each other intending to establish linear regression and correction factors. The two sets of instrumentation were put in parallel in the same environment inside a closed room for one hour where the loggers set to record data with one second interval. As a result, the differences between the readings and the average of the two sensors are within the specified resolution of the sensor (0.03°C), indicating acceptable similarity. On the other hand, the recorded relative humidity from the internal humidity sensor in the USB data logger shows that the differences between the recorded relative humidity and the average are within 0.2% limits. Although this exceeds the specified resolution of the sensor, the difference is acceptable as the resolution acquired by the methodology is 1.0%. However, the logger's batteries were changed after each case, just in case and to make sure collecting reliable data.

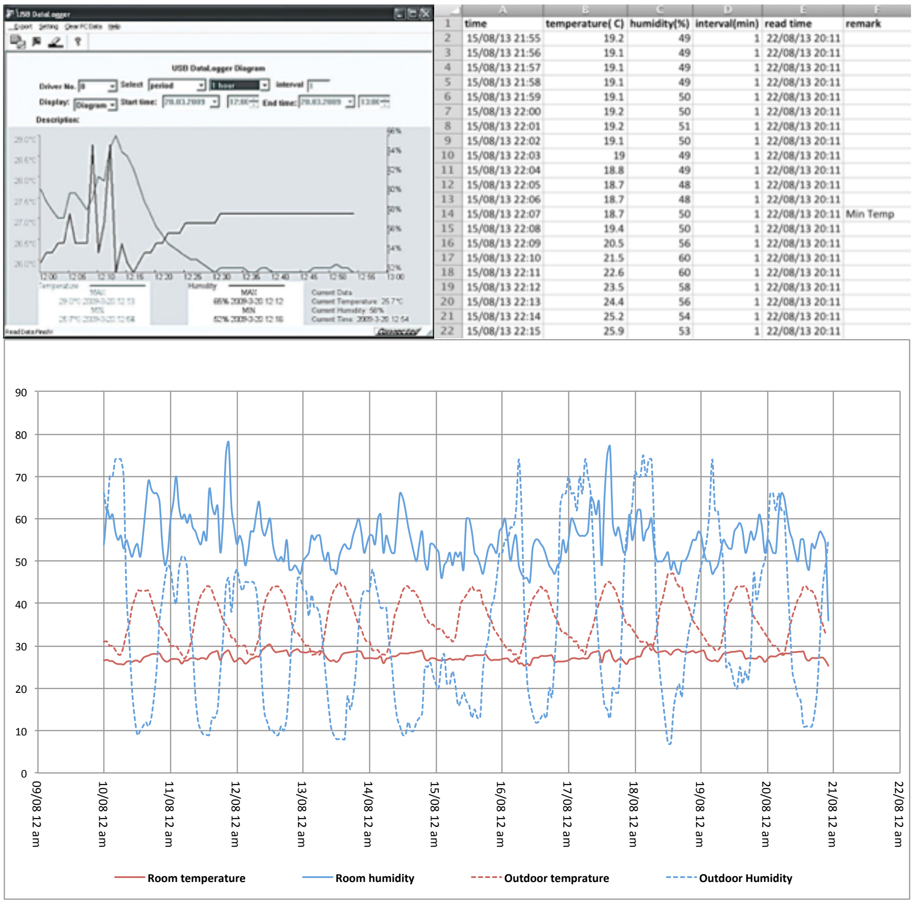
3.6.4 *Instrument software*

It is necessary with the enormous amount of data to transfer them for further analysis. As using Kestrel 4400 heat stress tracker in the transverse survey, the device comes with software that downloads the recorded data from the instrument. It has Integrated Bluetooth wireless and offers both real-time and logged data that can be transferred wirelessly and operated by Kestrel Interface. When the data is offloaded, the recorded data is initially presented in a form of comma-separated values (.csv). The downloaded data can easily be exported into programs such as Microsoft Excel, which allows converting the data to a table form or graphs.

Figure 3.3: The Kestrel 4400 measuring in the field work, attached to the tripod at a height of 1m (Source: the author)

Figure 3.4: The USB data logger fitted in the living room in one of the cases, (Source: the author)

With the KG100 USB data logger, the logged data can be easily transferred to the computer and operated by the USB data logger program. The software that comes with the device can download the recorded data from the loggers. When the data is offloaded, the recorded data is initially presented as a graph but it can also be displayed as a table of readings as well (Figure 3.5). The downloaded data can be exported into programs such as Microsoft Excel. For more examples see the Appendix V.



	time	temperature(C)	humidity(%)	interval(min)	read time	remark
2	15/08/13 21:55	19.2	49	1	22/08/13 20:11	
3	15/08/13 21:56	19.1	49	1	22/08/13 20:11	
4	15/08/13 21:57	19.1	49	1	22/08/13 20:11	
5	15/08/13 21:58	19.1	49	1	22/08/13 20:11	
6	15/08/13 21:59	19.1	50	1	22/08/13 20:11	
7	15/08/13 22:00	19.2	50	1	22/08/13 20:11	
8	15/08/13 22:01	19.2	51	1	22/08/13 20:11	
9	15/08/13 22:02	19.1	50	1	22/08/13 20:11	
10	15/08/13 22:03	19	49	1	22/08/13 20:11	
11	15/08/13 22:04	18.8	49	1	22/08/13 20:11	
12	15/08/13 22:05	18.7	48	1	22/08/13 20:11	
13	15/08/13 22:06	18.7	48	1	22/08/13 20:11	
14	15/08/13 22:07	18.7	50	1	22/08/13 20:11	Min Temp
15	15/08/13 22:08	19.4	50	1	22/08/13 20:11	
16	15/08/13 22:09	20.5	56	1	22/08/13 20:11	
17	15/08/13 22:10	21.5	60	1	22/08/13 20:11	
18	15/08/13 22:11	22.6	60	1	22/08/13 20:11	
19	15/08/13 22:12	23.5	58	1	22/08/13 20:11	
20	15/08/13 22:13	24.4	56	1	22/08/13 20:11	
21	15/08/13 22:14	25.2	54	1	22/08/13 20:11	
22	15/08/13 22:15	25.9	53	1	22/08/13 20:11	

Figure 3.5: The top left and right corner shows the interface of the KG100 USB logger program from which data can be exported as a .csv file, the data can then be illustrated in graphs in Excel (lower picture).

3.7 Summary

In order to explain the methodology that has been used in the research, this chapter has described the model of the method which was planned to establish the thermal comfort in Dammam's homes. The chapter has described the techniques that were explored for this research. It also included the criteria behind the design of the questionnaire and the reason behind using the informal interview. Finally, the instruments that have been used in the field work have been described. These details have been explained in this chapter in order to present in a clear way the link to the following chapter that describes the sequence of the experimental procedures of the research project.

CHAPTER FOUR: FIELDWORK PROCEDURE AND DATA COLLECTION

"The quality of a human environment can be measured only in terms of its effect on the people who experience it"

Edward Allen

4.1 Introduction

Conducting fieldwork in order to study people's thermal experience in their homes was never an easy task in such a culture and extreme climate as exists in Saudi Arabia. This chapter explains how this fieldwork was conducted, its procedure, and the form and nature of the data collected. The chapter has two parts: the first part deals with the procedure of the fieldwork, and the fieldwork plan and also describes the sample buildings in detail. The second part briefly outlines the results that were collected during the subjective survey from the occupants of their dwellings using the questionnaires. This part includes an overall summary of the results of the questionnaire, the transverse survey, the longitudinal survey, and the occupants' interviews. The remaining results, those collected from all forms of assessments, are analysed and evaluated in the following chapters five and six.

4.2 Preparation for the fieldwork and data collection

The process of data collection is based on multiple sources; while the spatial data sources are archival documents from governmental authorities and public agencies, such as past and present studies of housing in the city of Dammam, Saudi Arabia, statistical reports and design guidelines. However, the social and behavioural data sources were mainly collected through the questionnaire technique and interviewing the occupants. Therefore, through initial field work, to test the reliability of the methods used in the present research, the researcher had to do a pilot study before launching the real fieldwork.

The researcher was fortunate to conduct the pilot study during the yearly visit to Saudi Arabia in winter 2013, in the city of Dammam. The aim of conducting this pilot study in the same context as the proposed research was to obtain a clearer understanding of the advantages and limitations of the methodology used, both in the environmental measurements and comfort study, so these could be considered, avoided, or adjusted in advance. The other aim was to inquire in advance an arrangement for the availability of volunteers for the practical fieldwork, as in the summertime people normally travel to cool places.

4.3 Fieldwork experiments aim and objectives

Humphreys (1976) claims that the results of a field study may be regarded as the phenomena to be explained by theoretical models of thermal comfort. Discrepancies between the predictions of the theoretical models and the observations of field studies are valuable indicators of areas where our understanding of the subject is incomplete. A concise statement of the principal results of studies on the ground currently available is, therefore, appropriate here. Understanding the thermal comfort zone is very useful to enhance the design of buildings, specifically in homes, to avoid wasting energy, as occupants usually ignore controlling the energy they use while trying to acquire comfort. Therefore, the crucial aim of the fieldwork is to investigate the occupants' thermal experience and their preferences and behaviours in their dwellings, along with gathering the design drawings and energy consumption data of each dwelling. This aim is achieved through the following main objectives which originally form the research objectives (section 1.4):

1. To determine the neutral temperature in the summer and winter seasons and its relationship with indoor temperature.
2. To identify some of the adaptive behaviours used by people in their dwellings to ensure comfortable conditions.
3. To investigate the average energy consumption in existing Dammam homes and the operational cost of cooling these dwellings.
4. To explore the range of adaptive opportunities of the individual homes' design that could be exploited to achieve comfort.

4.4 Fieldwork procedure and strategy

Nicol (1993:49) , in his thermal comfort handbook for field surveys, states the difficulty in deciding the exact number of observations or subjects needed, but advocates as much data as possible for statistical analysis, and suggests that an adequate number would be twenty subjects providing 100 data sets each, but adds: "*if you can get more data sets without wearing out your subject so unduly extending the period over which the data is collected then do so*".

In this study:

a) The present fieldwork was carried out in 20 and 9 different residential buildings in the Eastern Region of Saudi Arabia in hot and cool season respectively.
b) Efforts were made to target typical dwellings so that they could be used as a model for other dwellings of similar characteristics and operation.

c) The questionnaire form was used to carry out data collection at the dwellings, with the respondents sitting with the researcher.
d) Furthermore, the subjects were selected randomly from different groups of people in Dammam (26.4° N, 49.9° E), i.e. educated, administrative and elite groups as well as average middle and lower income households, to represent a typical range of sample households.
e) Two sets of results were obtained from the strategy of applying both questionnaires and physical measurement, as has been discussed previously. A sample of nineteen dwellings was used for the subjective study. Surveys of seventeen homes were conducted in the hot season, during August 2013, and seven homes were surveyed in the cold season, during January 2014, with surveys of five homes carried out in both seasons.
f) An ignorance of Three cases from the hot season and two cases from the cool season datasets were ignored due to either the non-completion of the comfort survey or the incorrect readings of the loggers. So the total number was 19 homes where 5 homes conducted in both seasons.

The first step to implementing the field survey was to obtain permission to conduct the field experiment in each home, which was quite difficult without the prior arrangements. In addition to the pre-arrangements needed, the subject of thermal comfort is not familiar to the Saudi culture and many of the householders would not agree to conduct the field experiments in their homes. As a result, choices were limited to 20 homes those householders who permitted the researcher to conduct the field experiments without any conditions. Furthermore, due to the limited number of available instruments, the researcher then tried to arrange the volunteers in order to distribute the instruments to the cooperative volunteers during the month of August. In the first meeting, the researcher gave an introduction to the occupants of the homes, explaining the objectives of the research to be performed and its importance for the living environment. Participants were also assured that their identity would not be disclosed in the research. The questionnaires were made available in English as well as in Arabic, to further encourage participation in the research and only the Arabic version were used.

The researcher visited each householder to explain the project method and the integration between the loggers and the survey. In fact, there was a major problem when the researcher was going to visit any householder for a field survey, particularly in transverse sampling. This problem was that the occupants would immediately change their normal activity and clothing in the home, and dress formally during the visit due to religion and cultural reasons. Moreover, it was not possible for the researcher to meet the female occupants, therefore, some preparation was undertaken before all visits, such as:

1. A female assistant was charged to be with the researcher on a permanent basis and shared a clear image of the research aim, objectives and methods.
2. Explanation was provided to the subjects a day before by phone, as to what the survey consisted of and also they were asked if they preferred the attendance of the female assistant with the researcher.
3. Having once arrived at the dwelling, the equipment was placed in the suitable location, by the researcher, and the respondents were requested to complete the questionnaire in approximately 5-10 minutes.

For each home, the data was collected in three different stages. In the initial stage, information related to the building's physical and operational characteristics was collected, such as in-situ drawings of the building that the householder could provide and the energy data obtained from the home-owner; in fact, almost all householders did not have this information available at the time and suggested that they would email it to the researcher. Apart from the energy data, which was emailed by the owners, it was hard to obtain floor plans for all dwellings, due to the lack of assistance, as well as the availability of drawings. Therefore, with only the support of some individual occupants, the researcher had to take the dimensions of the floor plans and draw them manually alongside with the measurements of wall thicknesses, ceiling heights wall/window ratio, etc. Further information was obtained from the dialogue with the occupants, such as information about the adaptation of the dwelling design, openings, the HVAC system, and the operational cost of the dwelling. Collecting these data helped to develop the base case model in proximity to the real building. The second stage involved an objective assessment of air temperature, relative humidity, and air velocity through measurements at these dwellings. The last stage, a subjective assessment of thermal comfort was carried out involving the dwelling's users, to obtain their view regarding the prevailing indoor thermal comfort conditions.

The crucial question is how the environmental variables were measured. For this study, the KG100 USB Data loggers were placed in bedrooms and living rooms in each of the studied dwellings, to measure the environmental parameters, while at the same time the subjects would make a comfort assessment using a unique ComfApp on their smartphones. The data loggers were located in a place that was sufficiently away from windows, sunlight, cooling units and any heating source, such as TVs within the rooms and close to the normal occupied place.

After data collection in each dwelling, measurements were transferred from each data logger to a computer and saved, in order to avoid the risk of losing the readings for any reason. When the equipment was moved to the next dwelling, the batteries were changed in each device, to format the device to ensure more accurate measurements, and then the researcher connected it with another unique ComfApp to carry out another experiment.

In all the studied dwellings the air temperature and humidity were measured as environmental factors while the measurements were collected over an average of 10 days for each household. The recording interval was set to 5 minutes for all measurements. It is clear that there are limitations to the accuracy of the findings from such a set up. This is the reason for the concurrent questionnaire survey. A further limitation of the research was that there was only one Kestrel-4400 device, which was carried by the researcher, and the measurements, were taken at least twice for each household.

Timestamp	:المتطوع	المكان	الشعور	التفضيل	الرطوبة	الحركة	الأكل والشرب	الملابس	التكيف	هل فتحت الشباك أو أي تهوية خارجية منذ الإستبيان السابق؟
19/08 01:54 pm	[illegible]	الصالة	دفئ خفيف	لاتغيير	لايوجد رطوبة	أمشي في الخارج	لاشيء	ملابس داخلية, قميص طويل, جوارب طويلة, بنطال طويل	الستائر مغلقة, المروحة تعمل	لا
19/08 02:14 pm	[illegible]	غرفة النوم	دفئ خفيف	قليل من البرودة	رطوبة خفيفة	جالس وأعمل	لاشيء	ملابس داخلية, قميص طويل, جوارب طويلة, بنطال طويل	الباب مفتوح, الستائر مغلقة, التكييف يعمل	لا
19/08 03:22 pm	[illegible]	غرفة النوم	دفئ خفيف	قليل من البرودة	رطوبة خفيفة	جالس ومسترخي	لاشيء	ملابس داخلية, سروال طويل, ثوب	الشباك مفتوح, المروحة تعمل	نعم
20/08 05:22 am	[illegible]	غرفة النوم	برودة خفيفة	القليل من الدفئ	رطوبة خفيفة	جالس ومسترخي	لاشيء	قميص خفيف وقصير	التكييف يعمل	لا
20/08 07:54 am	[illegible]	A	دفئ خفيف	قليل من البرودة	لايوجد رطوبة	أمشي في الخارج	لاشيء	ملابس داخلية, سروال طويل, ثوب	الباب مفتوح, التكييف يعمل	لا
20/08 01:45 pm	[illegible]	غرفة النوم	دفئ	قليل من البرودة	رطوبة خفيفة	أمشي في الخارج	خفايف	ملابس داخلية, سروال طويل	الباب مفتوح, الستائر مغلقة, الأضواء مفتوحة, المروحة تعمل	لا

Figure 4.1: An example of the actual recording of the householder's mean votes by their smartphones in Arabic.

The total stored string was approximately 9000 readings of temperature and humidity for each measured room in all dwellings. Consequently, the whole dataset was huge in terms of numbers that were achieved, numbering approximately 300,000 readings. Following data collection in all the dwellings, the challenging stage was to match a specific indoor temperature and relative humidity with the outdoor temperature and relative humidity that would correspond with the actual mean votes. Therefore, as the differences between the indoor temperatures were very slight, the researcher reduced the interval between environmental readings to be one hour in order to make it readable when matching the data with outdoor temperatures and the 622 total subject's responses. Furthermore, the outside temperature and relative humidity at the time of each response were added to the data set, which was obtained from the weather station in Dammam city. Finally, the results were recompiled into an English version and encoded into numbers for the use of statistical analysis software in the last stage (Figure 4.2).

Timestamp	Subject	Place	Feelings vote	Preference	Humidity Feelings	Activity	Eating	Clothing	Room Control	Open window
19/08 01:54 PM	11	1	2	3	4	3	5	0.39	D, B	2
19/08 02:14 PM	11	2	2	2	3	1	5	0.39	A , F	2
19/08 03:22 PM	11	2	2	2	3	0	5	0.59	C, B	1
20/08 05:22 AM	12	2	4	4	3	0	5	0.18	A	2
20/08 07:54 AM	11	1	2	2	4	3	5	0.59	F, A	2
20/08 01:45 PM	11	2	2	2	3	3	2	0.12	F, D, E, B	2

Figure 4.2: The same above example, in figure 4.1, with the results encoded for the statistical work and the calculated *"clo"* value based on (Al-ajmi et al., 2008), see Appendix IV.

4.4.1 *Description of the case studies*

The fieldwork trip involved nineteen dwellings that varied in type and characteristics, some being individual apartments or villas, and were all characterised by mixed-method ventilation properties. All the respondents in this research who lived in the dwellings surveyed were Saudi nationals. These homes were occupied by middle-class families, with an average of 6 people in each household, distributed within a radius of 15 miles within and around the city of Dammam (26.4° N, 49.9° E), in the Eastern Region of Saudi Arabia (Figure 4.3). The field measurements and survey were carried out during August 2013 and January 2014.

The studied dwellings were chosen from a mixture of types, including villas, apartments, old design, new design, red brick and concrete block structure and were up to 30 years old. Figure 4.4 shows an example of these building types. The form, orientation, envelopes and construction of the dwellings and their HVAC systems were quite different from each other, as a result of being randomly selected. Some dwellings in the study had envelopes with very high thermal integrity, high levels of external wall insulation ranging between 20-30 cm wall thickness, double-glazing, minimal thermal bridging and efficient HVAC systems. Others had minimal or no insulation, a single glazing with air leaks, thermal bridges and inefficient cooling machines. Most of the homes had been built of typical concrete block construction, single/double block – externally rendered. All homes had operable windows, and almost all the occupants had potential visual contact with the outside.

Although the sample size means this group is not representative of the population of such dwellings as a whole in the eastern region, these particular dwellings have been selected as case studies to compare their environmental conditions and to establish some information on thermal comfort in this specific region.

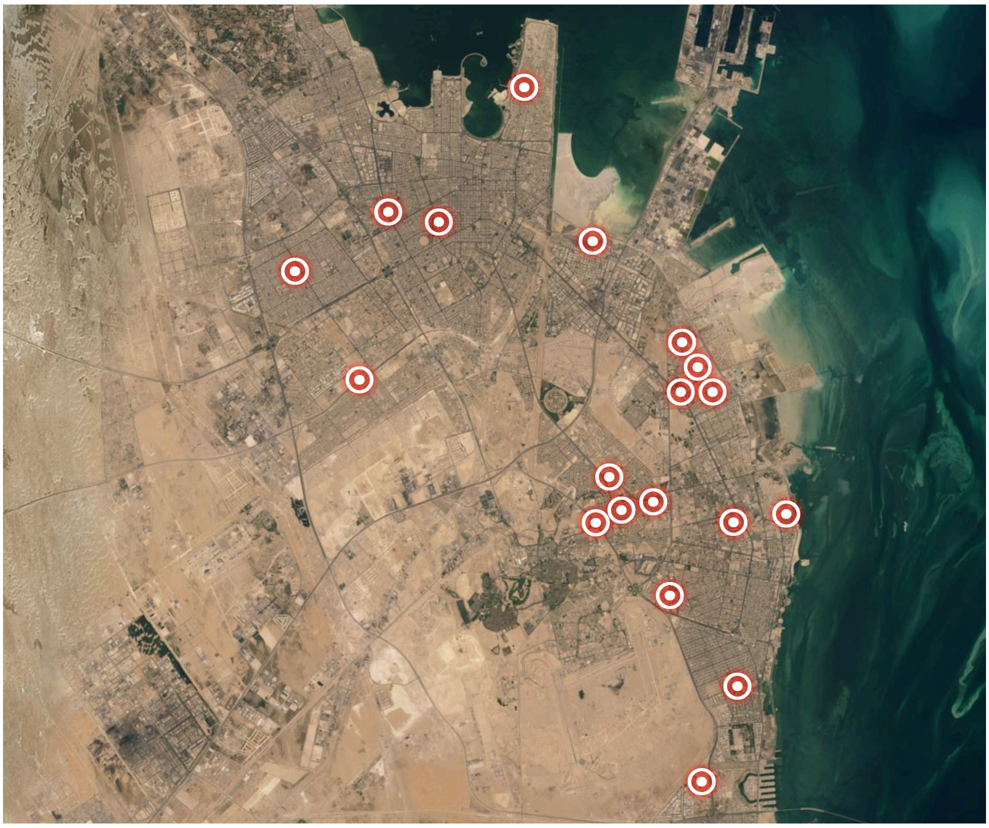


Figure 4.3: Map of the distribution of the locations of the cases in Dammam (26.4° N, 49.9° E), in the eastern region of Saudi Arabia (Source: Google Maps, 2016)

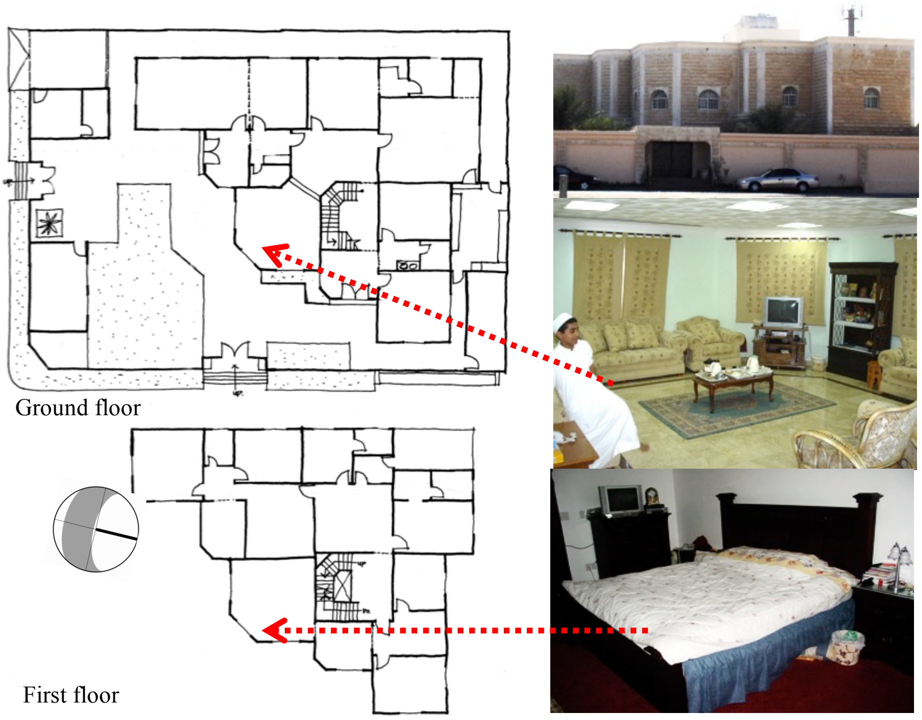


Figure 4.4: Typical example of the contemporary houses in Dammam, August 2013. The left hand shows the building site plan drawn by the researcher, while on the right are some photographs of the elevation and the measured living room and bedroom.

4.4.2 *The summer field trip*

These field experiments were carried out in Dammam during the extremely hot season of August 2013. After receiving the data loggers from the supplier in Dammam at the beginning of August, arrangements were made with the first phase householders to start the project. Obtaining permission to conduct field experiments in each home was the first step. As mentioned before, this was not easy to obtain, due to the fact that the thermal comfort subject being unfamiliar with local Saudi Arabian culture, and many of the householders approached did not agree to taking part in the field experiment. As a result, the choice was finally limited to twenty householders who permitted the researcher to conduct the field experiments. After obtaining permission from the twenty selected dwellings the field experiments were conducted in three phases as seven homes every ten days. In fact, after collecting the data, there were problems in three cases, in that they did not collaborate in filling in the survey at all, or moved the equipment from its place, so wrong measurements were gathered. Therefore, it was necessary to ignore these three cases in order to have clear readings and the total sample of the summer field trip was seventeen dwellings, instead of twenty as planned with a total of 472 actual comfort votes associated with around 1900 in door and outdoor environmental measurements.

4.4.3 *The winter field trip*

After the summer field experiment and the experience gained, another field experiment was carried out during the winter of January 2014. The aim of this fieldtrip was to gain data for the cool season to make a comparison with the summer data in terms of comfort experience and buildings performance. Similarly, to the experience in the summer, many people refused to cooperate again with the project mainly because they prefer not to take responsibility of the equipment and filling the survey. As a result, choices were very limited, to only seven householders, who permitted the researcher to conduct the field experiments again, in addition to another two, different, householders. Thus, the field experiments were conducted with just nine householders. In fact, as in the summer trip, it was discovered after collecting the data that two of the cases had not collaborated in filling in the survey at all. Thus, these two cases were disregarded and the total number of cases was seven dwellings, five of whom were also those surveyed during the summer field trip with a total of 89 actual comfort votes associated with more than 350 indoor and outdoor environmental measurements. Obtaining more data in the winter period was not possible, due to the midterm holiday, and many people were travelling or camping at this time of the year.

4.5 Following the fieldwork

After gathering all the data, it was a large task for the researcher to link the data loggers' stream to the survey results, based on the time stream. The researcher worked manually, looking carefully for the results from the data loggers and the data from the Dammam weather station to connect them with the survey outcomes.

4.6 Summary of the overall findings

The field surveys were completed with a total subject group of 39 people and the gender split was 19 and 20, between males and females respectively. The ages of the subjects ranged from twenty to over sixty years with a mean age of 37 years old. All subjects were in good health.

The measurements taken in the fieldwork, shown in Table 4.1, provide a valuable insight into the range of temperature experienced in the studied dwellings. During the fieldwork in August, the indoor air temperatures ranged from a low of 19.9°C to 39.3°C during the summer fieldtrip with an average of around 27°C. A single high report of 39.3°C was recorded in a unique event in one of the cases. On the other hand, during the cold season the indoor air temperatures ranged from a low of 18.2°C to 29.5°C, with an average of around 21°C.

The recorded humidity taken in the fieldwork indicates that it fluctuated from a low of 29% to a high of 84%, with an average of around 60% relative humidity in the hot season, while in in the cool season it fluctuated from a low of 59% to a high of 96%, with an average of around 79% relative humidity. These variations might be due to individual homes containing different humidity distributions created by the behaviour of the occupants (cooking, cleaning, bathing, use of dehumidifying HVAC etc.) which will modify the humidity, as well as the effect of outdoor humidity, which might account for a major share of the conditions. The mean relative humidity of the whole sample of 62.8% appears to be higher than the optimal standard of 55% followed as a rule of thumb by HVAC engineers for so long. Additionally, 80% of the data set experienced a relative humidity higher than 55%.

Table 4.1: The range of indoor air temperature (°C) and relative humidity (%) experienced in the studied dwellings of the present study in both seasons (*N* referred to the number of ComfApp readings in each case).

	Dwelling #		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**All**
hot season	***N***		**34**	**33**	**23**	**30**	**41**	**19**	**37**	**27**	**25**	**19**	**19**	**37**	**28**	**29**	**53**	**24**	**23**			**525**
	T_a	Mean	25.7	27.2	26.8	28.7	27.5	30.4	24.1	26.8	22.4	26.7	28.6	23.1	28.6	28.1	31.5	27.6	27.5			**27.1**
		Min	21.5	23.1	21.8	25.6	25.3	25.5	22.3	21.8	19.9	20.2	22.2	20.1	25.7	24.3	26	22.6	24.2			**19.9**
		Max	32.7	32.9	29.9	32.7	31.7	35.2	28.4	32.6	25.2	33.8	33.1	26.2	39.3	32.1	34.9	30.9	30.5			**39.3**
	RH	Mean	52.2	64.6	54.1	65.1	62.4	59.3	58.4	64.8	65	67.8	59.1	62.9	52.3	41.3	60.5	55.7	72.6			**59.9**
		Min	33	47	44	53	55	47	42	55	53	51	52	57	48	29	46	42	63			**29**
		Max	72	73	65	80	71	66	79	82	73	83	67	73	58	56	75	70	84			**84**
cool season	***N***		**16**		**11**	**10**	**9**							**13**						**22**	**14**	**97**
	T_a	Mean	20.6		22.3	20.4	20							19.5						24.5	21.8	**21.3**
		Min	18.6		21.2	19	19.1							18.2						20.8	18.5	**18.2**
		Max	29.5		23.9	21.5	20.6							20.8						26.7	25.1	**29.5**
	RH	Mean	84.1		75.4	81.5	68							84.7						78.2	80.5	**78.9**
		Min	69		71	73	59							76						68	68	**59**
		Max	87		87	92	77							94						86	96	**96**

The mean clothing values were 0.42 *clo* with a minimum of 0.05 *clo (only short Serwal with T-shirt)* and a maximum of 0.97 *clo (formal Saudi Thowb and Shemagh)* see Appendix III. However, in winter, the mean clothing values were 0.46 *clo* with a minimum of 0.12 *clo* and a maximum of 1.2 *clo.* About 60% of subject's clothing values were in the range of 0.05 *clo* to 0.41 *clo*. The mean metabolic rate was 0.67 *met* and 0.3 *met* during the hot season and cold season respectively.

The analysis of the summer field trip sensation responses shows that about 65% of subjects' votes in indoor conditions indicated one of the four top categories: between Hot and Neutral, and the mean sensation votes for all subjects on the ASHRAE scale were 3.32 (Slightly warm). Furthermore, almost the same portion of subject's preferences indicated they wanted more cooling to be more comfortable, which primarily shows that these people were not very satisfied with their environmental conditions in the summer.

However, in the cold season, the mean sensation votes for all subjects on the ASHRAE scale were 4.15 (Neutral). Furthermore, the mean of subject's votes on the preference scale indicated they wanted no change, which shows that these people were satisfied with their environmental conditions.

4.7 Summary

This chapter has focused on describing and explaining the procedures that were undertaken to conduct the field surveys in the city of Dammam, Saudi Arabia. It highlighted, at the beginning, the questionnaire preparation technique, and then described the field survey in terms of its design and the sample selection of case studies. This section was included in this chapter in order to link the present results gathered with the previous information in Chapters 1 Introduction and 4 The research methodology, in which the field survey methodology was introduced. In addition, some of the subjective results from the questionnaires have been presented. This preliminary analysis is based only on the occupants' reported results and their overall actual mean vote (AMV).

The results showed that, in their homes, the occupants were experiencing a variety of comfortable and uncomfortable time periods, which depended on the quality of their overall indoor climate. Further examination and analysis of these results will be carried out as the basis for the following chapters, 5, 6 and 7.

CHAPTER FIVE: FINDINGS AND ANALYSIS

"Findings, if potentially useful to the designer, are often communicated in a language she finds difficult to understand."

Sir Hugh Casson

5.1 Introduction

This chapter records the data that have been collected during the field surveys in Dammam during the summer and winter periods. It comprises two parts: The first section focuses on the results gathered during the subjective study from the occupants in their dwellings, by means of the questionnaire. The second part of this chapter analyses and evaluates all the available data regarding the thermal comfort survey, the physical environment and the energy consumption in each dwelling. All the measurements for thermal comfort requirements have been collected in the form of both subjective data and objective data (as explained previously in Chapter Four).

As mentioned in Chapter Two, the thermal comfort standards prescribed by EN ISO 7730 (1995) were the first to have been used on a worldwide basis. They are based on Fanger's work on climate chamber experiments that led to the PMV model, which is applicable to both naturally ventilated and air-conditioned buildings. However, the adaptive approach is adopted here to take into account also the range of adaptive opportunities and related actions that a people can, and do, take advantage of to achieve thermal comfort. Both approaches consider the same six basic parameters (i.e. four physical and two personal) as in the original PMV mode. However, the adaptive approach additionally considers the comfort temperatures in relation to outside air temperature, together with the behaviours of the occupants that influence their adaptation.

This chapter seeks to determine the extent to which existing research findings, correspond with the ISO 7730 standard which is based both on the Fanger PMV model (Fanger, 1970) and the adaptive model (Humphreys, 1976; Auliciems, 1983; de Dear et al., 1998; Nicol et al., 2012). A key question here is whether current models used to establish comfort conditions are appropriate for people who live in the extremely hot and humid climate of the Dammam region. The extent to which deviations from comfort conditions affect the degree of the discomfort of people in such environments is also explored.

In the following sections, a summary of the questionnaire findings will be introduced briefly, and an overview of the thermal comfort surveys will be followed by a discussion of the findings both the transverse and the longitudinal surveys including; the subject information, physical data, individual parameters, sensation responses, preference choices and humidity perceptions. This is followed by a primary analysis of the data, giving the relationship between the means of the variables, standard deviations and correlation coefficients, in order to demonstrate the nature and impact of a range of actions on the thermal sensations experienced in these Dammam homes. A detailed analysis of the performance of critical homes studied and the occupants' behaviour is undertaken in the following chapter. This allows for an evaluation of the efficacy and suitability of the different thermal comfort models and a discussion of their appropriateness for use in domestic fields surveys such as these in Dammam.

5.2 Questionnaire findings

The questionnaire was divided into four sections: demographic information, building type and personal profiles, occupant's thermal comfort in the whole building, general reported feeling and personal experiences.

5.2.1 *Demographic information*

The total sample of responses numbered sixty-one subjects for the general questionnaire, drawn from occupants of Dammam homes. All the participants were Saudi nationals and the age of the subjects ranged from 15 to over 60 years old, with a mean of 37 years old and with a gender split of thirty-four males and twenty-seven females. The majority of cohort dwellers were classified as belonging to the middle-income group, whose monthly income falls within the range of 10 to 20 thousand SAR (£1,800 to £3,600), which represents 40% of the total responses.

In addition, all subjects reported they were in good health, except four people who had high blood pressure and diabetes, which are chronic illnesses. Thirty percent of the total respondents claimed that they have respiratory problems and/or skin problems aggravated by the high temperatures. When calculating the body mass index of the responses, seventy-two percent of the research population were overweight (Table 5.2).

Table 5.1: Distribution of the participants' demographical data from the questionnaire

	Age						
Gender	15-20	21-30	31-40	41-50	51-60	over 60	**Total**
Male	1	9	10	6	6	2	**34**
Female	4	12	4	3	4		**27**
Total	**5**	**21**	**14**	**9**	**10**	**2**	**61**

Table 5.2: Distribution of the health condition and body mass index of the total participants *(each star represents an occupant with health issues aggravated at high temperature)*

BMI scale	Male	Female	Total
Underweight	3	1	**4**
Healthy weight	7*	3*	**10****
Slightly overweight	9	13*	**22***
Heavily overweight	15*	10	**25***
Total	**34****	**27****	**61********

Regarding the respondents' neighbourhood, 72% had lived in the same neighbourhood for more than ten years. 85% of the participants, reported, having a good relationship with their neighbours. Half of the contributors regarded their neighbourhood as safe, but around 23% considered the neighbourhood to be unsafe for their family's normal life.

Approximately 67% of the total respondents said they found the overall environment, including noise, neighbours, aesthetics and landscape acceptable for them. However, most of the criticism voiced by the remaining respondents focused on the extreme hot climate, as well as the ineffectiveness and deterioration of the local infrastructure of the neighbourhood, which a number of respondents felt was unfit for its purpose.

5.2.2 *Buildings and physical characteristics*

Of the people who participated in the questionnaire, 44 were living in houses/villas and 17 in apartments. Around 70% of the respondents have lived in their current home for less than 15 years, and 20% for more than 15 years. Only a quarter of the respondents were renting their dwellings, and the rest either owned their homes or were living in their parent's property.

The sizes of the majority of the homes are in the range of $300m^2$ to $800m^2$, and 20% are larger than $800m^2$. Half of the participants live in a double storey building while around 25% live in a single storey home and the rest of them in buildings with more than two storeys. The number of bedrooms in each home is dependent on the total area of the dwelling and not to the number of occupants in each dwelling. In terms of the home sizes and the number of bedrooms, therefore the majority of the respondents (35%) lived in homes which have between one and three bedrooms. However, the maximum number of bedrooms in a single home was nine, most likely allowing a sub-family to live in the same house. Additionally, the number of toilets is also dependent on the number of bedrooms in each home, where the maximum was twelve toilets, in the nine-bedroom home.

Regarding the design of homes, almost half of the participants did not like the overall design of their dwelling, and around 32% were dissatisfied with the interior design of the dwelling. Moreover, around half of the contributors reported that they felt more comfortable in their bedrooms while 40% preferred the thermal environment in their living rooms.

Turning to the type of the air conditioning system installed in dwellings, around 20% of the participants were using a central HVAC system only in their homes, while 10% and 40% operated Window AC units and Split AC units inside each room respectively; the remaining 30% have a combination of Split AC units and either Window AC units or central HVAC systems. However, only seven participants 10% had ceiling fans installed in their most occupied rooms as a useful technology to operate in between extreme seasons and they are rarely operated.

5.2.3 *Operating the AC system*

The majority of people stated that the decision to operate the AC over the year depends on the outside weather conditions. Table 5.3 shows that the majority of the participants operate the AC during the day-time from April until the end of November. At night-time, however, the majority start to operate their AC in May and switch them off by October every year. Moreover, looking to the electricity performance in Figure 5.14 supporting the statement that most people do not use the AC during November till March.

Table 5.3 Percentage distribution of people decides to operate and switch off the AC system over the day/night time annually.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Start to operate AC over daytime											
4.9%	8.1%	21.2%	26.3%	21.3%	8.2%						
								Start to switch off AC over daytime			
								22.9%	27.9%	29.4%	9.8%
Start to operate AC over night-time											
4.8%	4.9%	13.1%	26.1%	34.3%	6.5%						
								Start to switch off AC over night-time			
								32.8%	35.9%	14.6%	6.4%

Regarding the operational cost of the AC system and its maintenance issues, more than 60% claimed that the leading cause of the cooling device failure is the problem of dust clogging the machine. The cost of cleaning maintenance is directly related to the volume of dust accumulating over the year. There seems to be a fairly common misconception that householders think that the maintenance of the AC system is to only to mobilise the

Freon gas. In this research more than half of the participants just top up the Freon gas when it is reduced, without a regular check of the AC system, which consequently has a reduction on the overall efficiency of the cooling system efficiency in the long term and its electricity consumption.

However, householders appear not to be concerned about the cost of maintenance cost, as 60% responded it is not expensive to maintain the AC system. According to half of the participants, the average cost of maintaining a single cooling unit, which only covers the adding of Freon and cleaning dust from a single machine, is in the range of 200 to 300SAR (£55). However, around 30% of the participants claimed the cost is above 300SAR. In terms of frequency, 80% of the participants usually bring professionals to maintain their cooling system from once or twice a year. Taking the fact that maintaining a single unit costs around 300 SAR (£55), the price of a single maintenance service checks for the whole home, without the cost of failed parts, depends on the number of cooled rooms in each home, and ranges from around 1,500 SAR (£275) to 3,600 SAR (£660) for homes with five rooms and twelve rooms respectively.

5.3 Thermal comfort survey findings

5.3.1 *Thermal comfort survey*

As described in Chapter Four, the field study method using reported thermal comfort observations was used in this study. The following section will describe the findings of the field studies undertaken for this research.

5.3.1.1 Subject information

The sample for the comfort survey responses consisted of thirty-nine subjects, eighteen males and twenty-one females, distributed in nineteen Dammam homes. The total sample of survey responses obtained from those subjects numbered 561, drawn from nineteen homes in Dammam during the hot and the cool season. All participants were Saudi nationals, and the ages of the subjects ranged from 21 to 60 years old, with a mean age of 34. The largest group of the cohort are classified as belonging to the middle-income group, representing 44% of the total responses.

Apart from the four subjects who had chronic illnesses, all subjects were in good health during the time of the survey. Ten subjects reported that they had respiratory problems or a skin problem (five respondents for each) which was aggravated by high temperatures. In addition, 83% of those who participated in the longitudinal survey were overweight.

Table 5.4: Distribution of the demographic data and the body mass index of the participants included in the comfort survey *(each star represents an occupant with a health issue aggravated by high temperatures)*

Gender	Age	BMI			Total
		healthy weight	*slightly overweight*	*heavily overweight*	
Male	21-30	0	0	0	**0**
	31-40	3	1	3	**7**
	41-50	1*	1	2	**4***
	51-60	1	1	3*	**5***
	Total	**5***	**3**	**8***	**16****
Female	21-30	0	6	4	**10**
	31-40	0	1	1	**2**
	41-50	0	1	2	**3**
	51-60	1*	2*	1	**4****
	Total	**1***	**10***	**8**	**19****
Total	21-30	0	6	4	**10**
	31-40	3	2	4	**9**
	41-50	1*	2	4	**7***
	51-60	2*	3*	4*	**9*****
	Total	**6****	**13***	**16***	**35******

Table 5.5 Summary of personal information of the respondents included in the comfort survey.

Total number of dwellings			19
Average number of people in dwellings		*(person/bldg.)*	6.5
Gender	Male	*(person/bldg.)*	4.7
	Female	*(person/bldg.)*	3.2
Age	Adult	*(person/bldg.)*	3.7
	Children under 18	*(person/bldg.)*	2.6
Occupancy	Owner	(%)	77
	Tenant	(%)	23

5.3.1.2 Distribution of physical data

In this study, air temperatures and relative humidity were measured indoors and outdoors for both longitudinal and transverse surveys, whereas MRT (mean radiant temperature), air velocity, and globe temperatures were only collected at indoor conditions for the transverse survey. Summaries of the climatic data in terms of their means, ranges and standard deviation are tabulated in Table 5.6 for the hot and cool seasons. Perfect temperature control could not be expected, especially when all of the dwellings operated different AC systems, quite possibly with different temperature set points. Details of measurement protocols were included in Chapter Four (4.6).

Table 5.6 Means, standard deviation, minimum and maximum of both transverse (T) and longitudinal (L) survey environmental data in the hot (H) and cool (C) seasons.

		L.H.	**T.H.**	**L.C.**	**T.C**	**H. all**	**C. all**	**All**
Number of readings		*472*	*53*	*89*	*8*	*525*	*97*	*622*
Outdoor T_a (°C)	mean	35.9	37.7	14.5	14.8	36.1	14.5	32.7
	SD	5.4	3.7	3.7	3.2	5.31	3.62	9.34
	Min.	26.0	29.0	8.0	12.0	26	8	8
	Max.	47.0	45.1	22.0	19.0	47	22	47
Outdoor RH (%)	mean	35.4	30.2	70.0	66.5	32.8	68.25	50.53
	SD	22.1	21.4	16.1	17.2	21.75	16.65	19.2
	Min.	7.0	10.0	30.0	37.0	7	30	7
	Max.	94.0	79.0	100.0	82.0	94	100	100
Indoor T_a (°C)	mean	27.2	24.4	21.6	24.1	26.87	21.80	26.08
	SD	3.4	2.9	2.4	2.4	3.46	2.50	3.80
	Min.	19.9	21.4	18.2	20.1	19.90	18.20	18.20
	Max.	39.3	33.6	29.5	27.1	39.30	29.50	39.30
Indoor RH (%)	mean	59.7	52.3	79.4	65.1	58.98	78.19	61.98
	SD	9.6	11.5	7.7	7.0	10.05	8.58	12.05
	Min.	29.0	23.0	59.0	56.2	23	56.2	23
	Max.	84.0	82.0	96.0	76.4	84	96	96
Mean radiant temperature (°C)	mean		27.7		24.0			27.2
	SD		5.3		2.4			5.2
	Min.		20.6		19.4			19.4
	Max.		39.2		26.4			39.2
Air velocity (m/s)	mean		0.3		0.3			0.3
	SD		0.2		0.5			0.3
	Min.		0.1		0.0			0.0
	Max.		1.0		1.6			1.6
Globe temperature (°C)	mean		26.6		23.0			26.1
	SD		4.8		3.4			4.8
	Min.		19.7		15.5			15.5
	Max.		38.5		26.1			38.5

T.H. = Transverse finding in hot season L.H. = Longitudinal finding in hot season
T.C. = Transverse finding in cool season L.C. = Longitudinal finding in cool season
H. all = The total findings of the hot season C. all = The total findings of the cool season

Indoor air temperature ranged from a low of 18.2°C to a high of 29.5°C during the cool season. The low and high temperatures during the hot season ranged from 19.9°C to an outlier of 39.3°C, similar to a normal distribution. The temperature average was 26.87°C in the hot season and 21.8°C for the cool season, with 5K difference between seasons, which allows an excellent opportunity to obtain significant results in this study.

The measurements taken in this field study provide a valuable insight into the range of humidities experienced in the dwellings under study. The minimum and maximum measured indoor humidity in the data set ranges from 23% to 84% and 56.2% to 96%, for the hot season and cool season respectively. The mean RH of the whole sample of around 62% appears to be higher than the optimal standard of 55% followed as a rule of thumb by HVAC engineers for so long (see section 2.3.5). The humidity measurements indicate values highly at risk of very high dust mite populations which would indicate the probability of higher than normal concentrations of mould spores. The level of humidity experienced in bedrooms in the cool seasons shown in Table 5.7, precisely, is very concerning which indicates that some people at higher risk of health problems during bedtime and the level of danger depends on the humidity experienced and the health condition of those people.

Regarding the mean radiant temperature (MRT) measured during the researcher's visit to each home, this ranged from a low of 19.4°C to a high of 26.4°C during the cool season. The low and high mean radiant temperature during the hot season ranged from 20.6°C to 39.2°C. It is noticeable that the MRT in summer are significantly higher than measured air temperatures, augmenting the cases for more radiant cooling. The mean of the MRT was around 27.2°C in the hot season, with around 3K difference between hot and cool seasons, which is fairly lower than the difference in the indoor temperature means. For the globe temperature, maxima of 38.5°C in the hot season and 26.1°C in the cool season were recorded. The mean globe temperatures were 26.6°C and 23°C for the warm and cool seasons respectively.

Table 5.7 Mean, standard deviation, minimum and maximum of the indoor air temperature and indoor humidity distributed by living room and bedrooms in the hot and cool seasons, measured among dwellings in the longitudinal survey.

		Hot season			**Cool season**		
		Living rooms	Bedrooms	All	Living rooms	Bedrooms	All
T_a	Mean	27.74	26.05	26.87	21.96	21.57	21.8
	SD	3.34	3.38	3.46	2.59	2.37	2.5
	Min.	20.2	19.9	19.9	18.6	18.2	18.2
	Max.	39.3	35.2	39.3	29.5	25.4	29.5
RH	Mean	58.24	59.68	58.98	76.39	80.87	78.19
	SD	9.48	10.53	10.05	8.53	8.04	8.58
	Min.	33	23	23	56.2	58.6	56.2
	Max.	82	84	84	94	96	96

The average air velocity (m/s) measured in the dwellings during the researcher visits was alike in both cool and hot seasons, at 0.3 m/s. The maximum measured air velocities were 1.6 m/s and 1 m/s during the cool season and hot season respectively. It is noticeable that the air speed is higher in the cool season, as it influenced by the outdoor air movement, due to the opening of windows, whereas the AC controls the movement of air in the rooms in summer, so it might be beneficial to stimulate the air movement this season by the use of ceiling fans.

5.3.1.3 Distribution of individual parameters

Clothing value, as expressed in physical data, has a significant effect on thermal comfort. It differs from one individual to another. Table 5.8 and Table 5.9 present the summary of clothing information and metabolic rates found during the two experimental studies.

The mean clothing value of the occupants of Dammam homes was 0.43 *clo*. Not surprisingly, the amount of the average value of clothing had been increased in the cool season by 7%. Differences between local clothing in summer and winter are an important point, especially in adaptation behaviour. In the cool season, the maximum clothing value was 1.2 *clo*: being in a high level of clothing insulation it is bearable to look more elegant. For example, the usual male clothing wear is a coloured wool THOUB and SHOMAGH that has a 0.7 *clo* value or for women DARRA'AH is the usual dress (see section 2.3.7), which has 0.9 *clo* value. In the hot season, however, the average of clothing insulation for all groups was 0.42 *clo*, with the range of a minimum of 0.05 *clo* and maximum of 0.97 *clo*.

Table 5.8 Mean and standard deviation of clothing rate distributed by the occupied rooms during the hot and cool seasons, estimated among the longitudinal survey respondents.

clo.	**Hot season**			**Cool season**		
	Living rooms	Bedrooms	All	Living rooms	Bedrooms	All
Mean	0.48	0.36	0.42	0.53	0.43	0.49
SD	0.24	0.22	0.24	0.30	0.23	0.28
Min.	0.12	0.05	0.05	0.12	0.12	0.12
Max.	0.97	0.9	0.97	1.2	0.95	1.2

Table 5.9 Mean and standard deviation of metabolic rate distributed by the occupied rooms during the hot and cool seasons, estimated among the longitudinal survey respondents.

met.	**Hot season**			**Cool season**		
	Living rooms	Bedrooms	All	Living rooms	Bedrooms	All
Mean	0.81	0.53	0.67	0.31	0.29	0.30
SD	0.92	0.83	0.89	0.54	0.46	0.51
Min.	0	0	0	0	0	0
Max.	1.2	1.2	1.2	1	0	1

As shown in Table 5.9, the metabolic rate varied among all groups, with a relatively high standard deviation. It seems the environmental conditions have a slight influence on the activities. The data shows that people in the cool season are less active than in the hot season. The mean metabolic rate for all males and females in all seasons was less than 1 *met* which means that people usually do passive work in their homes. Surprisingly, it shows also that females are slightly less active in homes than males, which might be related to the fact that they stay at homes more than males.

5.3.1.4 Distribution of sensation responses and preference choices

The distribution of sensation responses for both seasons is shown in Table 5.10, Table 5.11, and Figure 5.1. The boxplots and dot plots in Figure 5.2 and Figure 5.3 shows the ASHRAE seven-point thermal sensation scale for both seasons with a statistical summary of the indoor air temperatures associated with those ASHRAE responses on the right hand. The first and significant point is that just over 70% of subject responses during both seasons in indoor conditions indicated one of the three central categories, which is in the comfortable zone in Bedford's scale terms, slightly cool, neutral and slightly warm. Around 36% of Dammam householders reported being in a neutral condition during the cool season, while just 29% of subjects reported feeling neutral in the hot season. The mean sensation vote in the cool seasons is quite similar to the hot season. The mean sensation responses on the ASHRAE scale were (neutral) 0.02 and 0.15 in the hot and cool season respectively. One reason may be that the difference between the average indoor air temperature in both seasons is around 5K. Another reason may due to the different expectations of the experienced indoor temperature in the respective seasons which leads to fairly similar responses to the ASHRAE scale.

Table 5.10 Mean and standard deviation of ASHRAE sensation responses in both seasons and both transverse and longitudinal survey

ASHRAE	**Hot season**			**Cool season**		
	Living room	Bedroom	All	Living room	Bedroom	All
Mean	0.28	-0.23	0.02	0.17	0.13	0.15
SD	1.35	1.40	1.40	1.19	1.32	1.24
Min.	-3.00	-3.00	-3.00	-2.00	-2.00	-2.00
Max.	3.00	3.00	3.00	2.00	3.00	3.00

Table 5.11 Distribution of ASHRAE thermal sensation responses in both seasons and both transverse and longitudinal survey

ASHRAE sensation scale		**Hot season**		**Cool season**	
		N	%	N	%
Hot	(+3)	13	2.50%	3	3%
Warm	(+2)	82	15.74%	12	12%
Slightly warm	(+1)	85	16.31%	19	20%
Neutral	(0)	149	28.60%	35	36%
Slightly cool	(-1)	132	25.34%	19	20%
Cool	(-2)	40	7.68%	9	9%
Cold	(-3)	20	3.84%	0	0%

Responses to the preferences scale, as shown in Table 5.12 and Table 5.13, were 38.7% preferring "no change", 55.4% voting for cooler and only 5.9% voting for warmer, during the hot season. In the cool season, however, the preference scale responses were 47.2% preferring "no change", 17.5% preferring to be cooler and 35% voting for warmer. From both field studies, there were 49.5% preferring "no change" while 49.5% preferred cooler and 10.5% preferred to be warmer. Furthermore, no one in the hot season responded preferring much warmer and only one single response to be much cooler was recorded in the cool season.

Around 70% of subject responses were within the central three categories on the ASHRAE scale. The range of indoor air temperatures recorded during the two experiments was 18.2°C to an outlier of 39.3°C; there were very slight responses on either extreme sides in reported sensation choices.

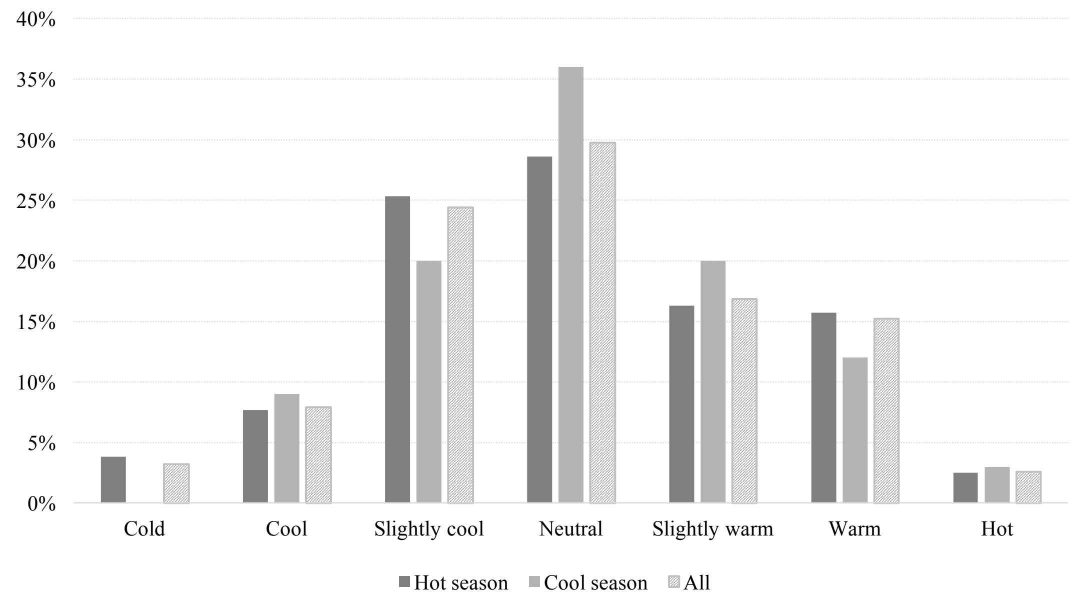


Figure 5.1 Histogram of the sensation responses distribution in both seasons

Table 5.12 Distribution of preference choices in both seasons and in all homes and both type of survey.

Preferences scale		Hot season		Cool season		All	
		N	%	N	%	N	%
Much cooler	(-2)	135	25.71%	1	1.03%	136	21.86%
A bit cooler	(-1)	156	29.71%	16	16.49%	172	27.65%
No change	(0)	203	38.67%	46	47.42%	249	40.03%
A bit warmer	(+1)	31	5.90%	23	23.71%	54	8.68%
Much warmer	(+2)	0	0.00%	11	11.34%	11	1.77%

Table 5.13 Mean and standard deviation of preference choices in all seasons and both type of survey.

Preference	Hot season			Cool season			All		
	Living room	Bedroom	All	Living room	Bedroom	All	Living room	Bedroom	All
Mean	-0.90	-0.61	-0.75	0.22	0.36	0.28	-0.69	-0.49	-0.59
SD	0.92	0.87	0.91	0.88	0.96	0.91	1.01	0.94	0.98
Min.	-2.00	-2.00	-2.00	-1.00	-2.00	-2.00	-2.00	-2.00	-2.00
Max.	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00

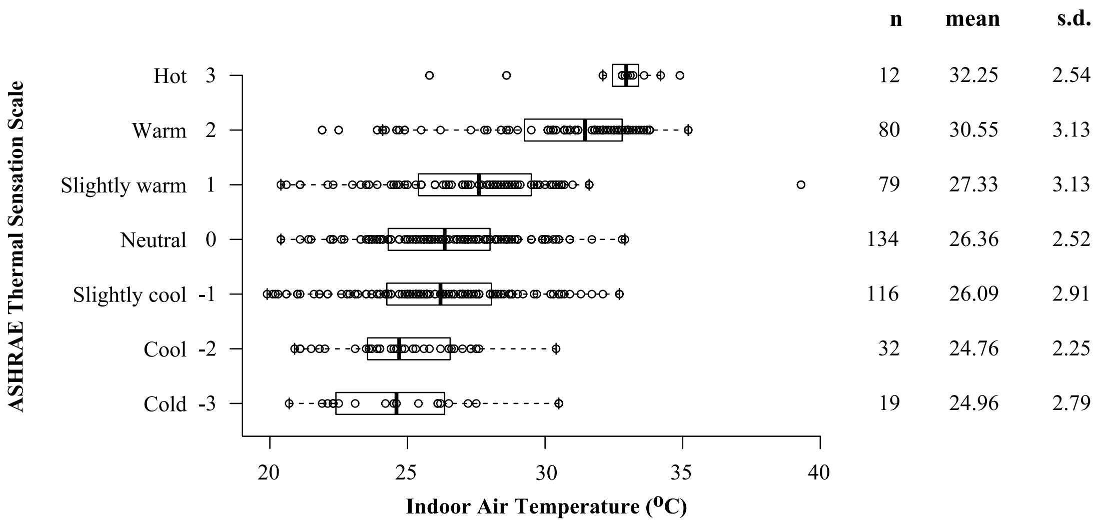


Figure 5.2: Boxplots and dot plots of the summer ASHRAE thermal sensation (ASHRAE seven-point scale), and on the right hand scale, a statistical summary of the indoor air temperatures associated with those ASHRAE responses (°C) in the longitudinal survey.

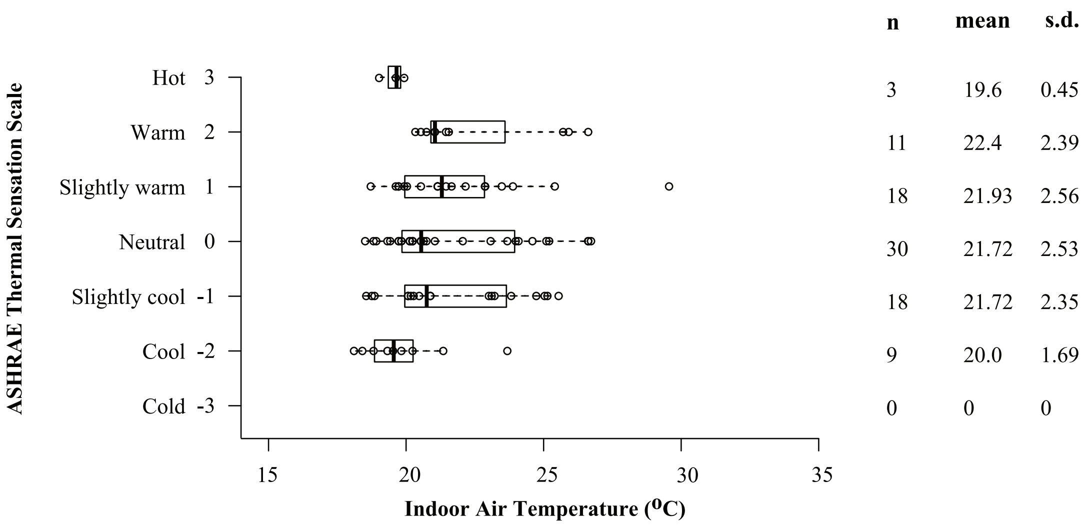


Figure 5.3: Boxplots and dot plots of the winter ASHRAE thermal sensation (ASHRAE seven-point scale), and on the right hand scale a statistical summary of the indoor air temperatures associated with those ASHRAE responses (°C) in the longitudinal survey.

From Figure 5.2 and Figure 5.3 we can see the distribution of the total responses of occupants of the nineteen homes during both seasons, where the largest group of the occupants described themselves as being thermally neutral. It can be seen that, of the total longitudinal valid responses, 134 of the occupant's responses described themselves as being thermally neutral during the hot season, and 30 in the cool season. In summer, 79 of the occupant's responses were slightly warm whereas 116 were slightly cool. Interestingly, 92 of the reported responses, or close to 20% of the dataset, were feeling warm or hot, and half of these votes were while experiencing a temperature equal to or above 30°C.

5.3.1.5 Distribution of humidity perception responses

Reported responses to the perception of humidity paint a complex picture. There is no actual reported sensitivity to humidity as such, as there is with temperature. It is the impact of humidity that the respondent may have perceived, i.e. the presence of sweat and the slightly increased sense of warmth in the heat. In attempting to understand the occupants' perceptions of humidity in their surroundings, called in this study "humidity perception", it was felt to be important to explore how sensitive the occupants are in their perception of individual objective parameters, or how they felt them.

The distribution of sensation votes for both seasons is shown in Table 5.14 and Table 5.15. The first and significant point is that 62% of subject responses during both seasons in indoor conditions indicated that it was "not humid" and only around 29% of subjects indicated that it was "a bit humid". The mean sensation humidity choice in the cool season is quite similar to the hot season, even though the range of experienced RH in both seasons is not the same.

Table 5.14 Distribution of humidity perception responses in both seasons and in all homes

Humidity perception scale		Hot season N	%	Cool season N	%	All N	%
Not humid	(1)	289	51.5%	56	10%	345	61.5%
A bit humid	(2)	140	25%	24	4.3%	164	29.2%
Humid	(3)	28	5%	7	1.2%	35	6.2%
Very humid	(4)	15	2.7%	2	0.4%	17	3%

Table 5.15 Mean and standard deviation of humidity perceptions responses in both seasons

Humidity per.	Hot season			Cool season			All		
	Living room	Bedroom	All	Living room	Bedroom	All	Living room	Bedroom	All
Mean	1.57	1.45	1.51	1.44	1.59	1.49	1.55	1.47	1.51
SD	0.81	0.68	0.75	0.66	0.86	0.74	0.78	0.71	0.75
Min.	1	1	1	1	1	1	1	1	1
Max.	4	4	4	4	4	4	4	4	4

5.3.2 *Relationship between mean of variables*

Figure 5.4 and Figure 5.5 show the scatter diagrams of air temperatures with mean sensation responses and preference choices in all response groups during both seasons. There is a high and positive relationship between air temperature and thermal sensation responses, the higher the temperatures the warmer the sensation. Such a relationship also exists between air temperatures and preference choices, but is negative.

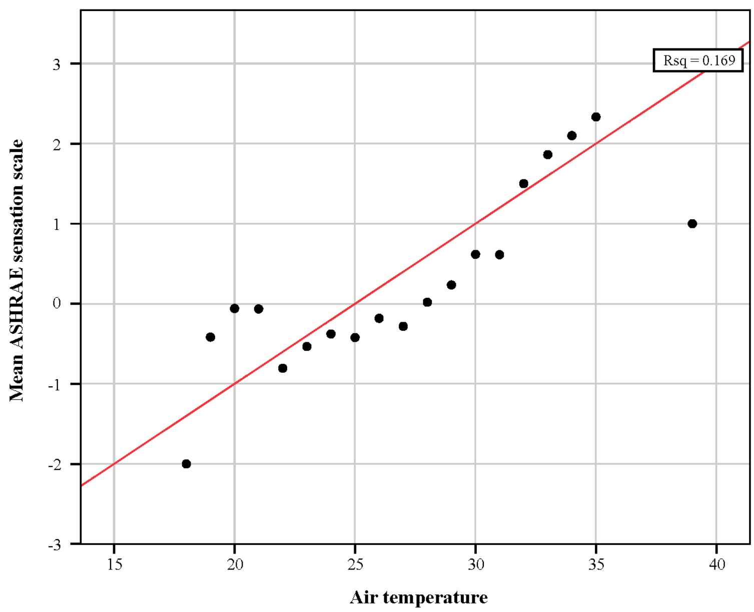


Figure 5.4 Relation between air temperature and mean ASHRAE sensation, binned by air temperature responses in both seasons and all groups

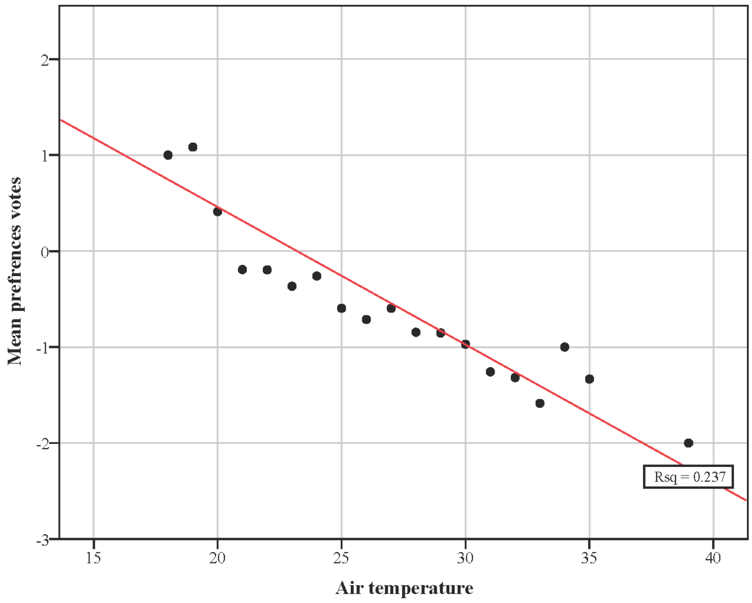


Figure 5.5 Relation between air temperature and mean preference choices in both seasons and all groups

5.3.3 *Standard deviation*

The standard deviation of different environmental data allows comparison of their impact with respect to locations and variability and enables the following conclusion to be drawn:

1. Air temperatures in the hot season have a greater variability than the air temperature in the cool season. However, the sensation responses of subjects in the hot season are higher than in the cool season showing that people are more sensitive to experienced air temperatures in the hot season.
2. Variability of relative humidity in the hot season was greater than in the cool season. The humidity perception in living rooms was higher than in bedrooms, in the hot season, and vice-versa in the cool season, showing that people's sensitivity to humidity was greater in bedrooms in the cool season and living rooms in the cool season.
3. The standard deviation reflects a reasonable equality between respondents, with a standard deviation of sensation responses of 1.4 and 1.2 for the hot and cool seasons respectively.
4. Standard deviations of clothing values in both seasons were great, showing that people were using different clothing assemblages according to the locations and needs, which indicates the presence of adaptation to either environmental conditions or cultural requirements.

5. Standard deviation of the metabolic rate of 0.9 and 0.5 for the hot season and cool season respectively, shows that people are less active in the cool season which might be related to the low temperature experienced.

5.3.4 *Correlation coefficient*

The correlation coefficient is a statistical method used to investigate the relationship between two variables. A correlation coefficient of (+1) or (-1) implies that all the points fall on a straight line; when it is equal to zero (0) they are scattered and give no evidence of a linear relationship. Any other value between (-1) and (+1) suggests the degree to which the points tend to be linearly related. The square of the correlation coefficient gives a measure of the proportion of the variation of the value of the variable which can be explained by the variation of the other value. It is noticeable that the correlation coefficients in the present study signify a statistically significant level < 0.01, 0.05 and 0.001.

5.3.4.1 Correlation between the environmental variables

The correlations of the environmental variables (outdoor air temperatures, outdoor relative humidity, indoor air temperature and indoor relative humidity) were relatively high during the hot season but there was a very low correlation in the cool season. This is reasonable because of the relatively highly range of humidity, with a warm range of air temperature (between 19.9°C – 39.3°C) during the hot season as well as in the cool season the effect of outdoor condition is fairly high and all points fall in a straight line. However, it shows a high correlation between the indoor air temperature and indoor relative humidity in all seasons. The potential of the inside wall thermal insulation as well as activities inside the house, such as cooking and having a shower, do not appear to have an effect on these correlations.

Table 5.16: Correlation coefficients between environmental variables, measured within the longitudinal survey

	Hot season	Cool season	All
$T_{a\ outdoor}$: $T_{a\ indoor}$	0.442	0.069	-0.056
P=	*0.000*	*0.502*	0.671
$T_{a\ outdoor}$: RH_{indoor}	-0.503	-0.134	-0.435
P=	*0.000*	*0.189*	0.000
$RH_{outdoor}$: $T_{a\ indoor}$	-0.237	-0.084	0.221
P=	*0.000*	*0.416*	0.087

$RH_{outdoor}$: RH_{indoor}	0.350	-0.05	0.345
P=	*0.000*	*0.628*	0.006
$T_{a\ indoor}$: RH_{indoor}	-0.307	-0.418	0.24
P=	*0.000*	*0.000*	0.063

Table 5.17 Correlation coefficients between environmental variables, in the sixty-one transverse data collected

	Hot season	**Cool season**	**All**
$T_{a\ outdoor}$: $RH_{outdoor}$	-0.792	-0.823	-0.749
P=	0.000	0.012	0.000
$T_{a\ outdoor}$: $T_{a\ indoor}$	-0.201	-0.348	-0.056
P=	0.149	0.398	0.671
$T_{a\ outdoor}$: RH_{indoor}	-0.280	0.012	-0.435
P=	0.042	0.977	0.000
$T_{a\ outdoor}$: $T_{g\ indoor}$	0.056	-0.275	0.243
P=	0.692	0.509	0.059
$T_{a\ outdoor}$: MRT_{indoor}	0.093	-0.355	0.248
P=	0.506	0.388	0.054
$T_{a\ outdoor}$: V_{indoor}	-0.191	0.026	-0.028
P=	0.171	0.950	0.830
$RH_{outdoor}$: $T_{a\ indoor}$	0.289	0.172	0.221
P=	0.036	0.685	0.087
$RH_{outdoor}$: RH_{indoor}	0.204	0.090	0.345
P=	0.143	0.831	0.006
$RH_{outdoor}$: $T_{g\ indoor}$	0.160	0.267	0.009
P=	0.253	0.523	0.944
$RH_{outdoor}$: MRT_{indoor}	0.102	0.435	-0.026
P=	0.465	0.281	0.841
$RH_{outdoor}$: V_{indoor}	-0.117	0.005	-0.086
P=	0.404	0.990	0.508
$T_{a\ indoor}$: RH_{indoor}	0.302	-0.172	0.240
P=	0.028	0.684	0.063
$T_{a\ indoor}$: $T_{g\ indoor}$	0.692	0.704	0.678
P=	0.000	0.051	0.000
$T_{a\ indoor}$: MRT_{indoor}	0.715	0.525	0.689
P=	0.000	0.182	0.000
$T_{a\ indoor}$: V_{indoor}	0.068	-0.655	-0.072
P=	0.631	0.078	0.580
RH_{indoor}: $T_{g\ indoor}$	0.157	0.431	0.061
P=	0.262	0.286	0.640
RH_{indoor}: MRT_{indoor}	0.139	0.635	0.052
P=	0.321	0.091	0.690
RH_{indoor}: V_{indoor}	-0.078	-0.397	-0.117
P=	0.579	0.330	0.370
$T_{g\ indoor}$: MRT_{indoor}	0.971	0.939	0.968
P=	0.000	0.001	0.000
$T_{g\ indoor}$: V_{indoor}	-0.028	-0.846	-0.147
P=	0.843	0.008	0.259
MRT_{indoor}: V_{indoor}	0.083	-0.782	-0.013
P=	0.554	0.022	0.920

5.3.4.2 Correlation between, sensation responses, preferences, humidity perception and other variables

The correlation coefficients of the thermal sensation responses with the preference choices and environmental data are presented in Table 5.18.

The correlation between sensation and preference is relatively high, as expected. The sensation responses also are well correlated with air temperature during the hot season, while there is very low correlation during the cool season, which might be related to the role of outdoor condition. Furthermore, it seems that the correlation of preference with air temperature is high, similarly to the sensation responses.

Regarding humidity perception, shown in Table 5.19, a relatively high correlation between humidity perception and indoor temperature and thermal sensation instead of the relation to the RH is demonstrated. It seems that the concept of humidity perception is misunderstood by respondents.

Table 5.18 Correlation coefficient of the ASHRAE sensation responses, preference choices and environmental variables, measured within the longitudinal survey

	Hot season	Cool season	All
Sensation: *Preference*	-0.505	-0.418	-0.441
P=	*0.000*	*0.000*	*0.000*
Sensation: $T_{a\ indoor}$	0.534	0.158	0.414
P=	*0.000*	*0.061*	*0.000*
Sensation: RH_{indoor}	0.061	-0.242	0.041
P=	*0.081*	*0.008*	*0.155*
Preference: $T_{a\ indoor}$	-0.394	-0.244	-0.488
P=	*0.000*	*0.008*	*0.000*
Preference: RH_{indoor}	-0.028	0.115	0.215
P=	*0.262*	*0.131*	*0.000*

Table 5.19 Correlation coefficient of the humidity perception choices, environmental variables and sensation responses, measured within the longitudinal survey.

	Hot season	Cool season	All
H perception: RH_{indoor}	0.342	0.104	0.308
P=	*0.000*	*0.166*	*0.000*
H perception: $T_{a\ indoor}$	0.220	-0.403	0.129
P=	*0.000*	*0.000*	*0.001*
H perception: *Sensation*	0.204	0.290	0.165
P=	*0.000*	*0.003*	*0.000*

The main conclusions drawn from this section are as follows:

1. The correlation between sensation responses and preference choices was relatively high.
2. The sensation responses had a good and highly significant correlation with air temperature; the preference choices also had a good and negative correlation with air temperature.
3. Humidity perception, surprisingly, is more correlated with indoor air temperature and thermal sensation, instead of relative humidity, as people may have misinterpreted the humidity feeling as a sensation of high temperature. Another reason might be related to the small amount of air movement with high RH associated with moderate temperature, reported as uncomfortable as stated by Victor Olgyay (1963).

5.3.5 *Regression analysis*

One recognised method to predict the subjective comfort which results from a given temperature or combination of environmental variables is regression analysis (Nicol et al., 2012). Giving the internal temperature and the subject thermal vote, the simple linear regression is formulated by the simple equation:

$$\boldsymbol{Y = aX + b} \tag{5.1}$$

where (in a thermal comfort study):

- Y = the thermal response
- X = the air temperature
- a = the slope
- b = the regression constant

For most purposes the neutral line (0) crosses the prediction line: a line is projected down to the temperature at which the line cuts the temperature axis.

Table 5.20 Data from simple linear regression for both seasons

	n	Slope	Intercept	R^2	T_n	Equation
Hot season	525	0.22	-5.779	0.285	26.7	$= 0.22\ T_a - 5.779$
Cool season	97	0.08	-1.55	0.025	19.9	$= 0.08\ T_a - 1.55$
All	**622**	**0.15**	**-3.865**	**0.171**	**25.8**	$\mathbf{= 0.15\ T_a - 3.865}$

A simple linear regression was performed on the reported ASHRAE scale responses versus air temperature responses to determine the strength of the relationship between them. Table 5.20 shows the comfort equations in two seasons. The slope of sensation lies around 0.15°C in all seasons (between 0.08°C and 0.22°C in Dammam homes during hot and cool seasons respectively). These slopes are less steep than the most common regression slopes of 0.25°C in a field survey in Pakistan, reported by Nicol (1993), as well as those of 0.22°C in the world- wide field studies reviewed by Humphreys (1976).

According to Humphreys (1976) the lower values of the slope suggest the occurrence of adaptation of respondents to their thermal environments. The neutral temperature during the hot season was 26.7 °C and during the cool season was 19.9°C. The scatter diagrams and the regression lines of the thermal sensation of all subjects during both seasons are presented in Figure 5.6. A high correlation coefficient between air temperature and sensation responses indicates a well-fitting regression line between them.

As with previous calculations of neutral temperature in this thesis, a simple linear regression analysis is used with two important points: thermal sensation responses as the dependent variable and air temperature as independent variable. Figure 5.6 show the scatter diagram of sensation responses and air temperature.

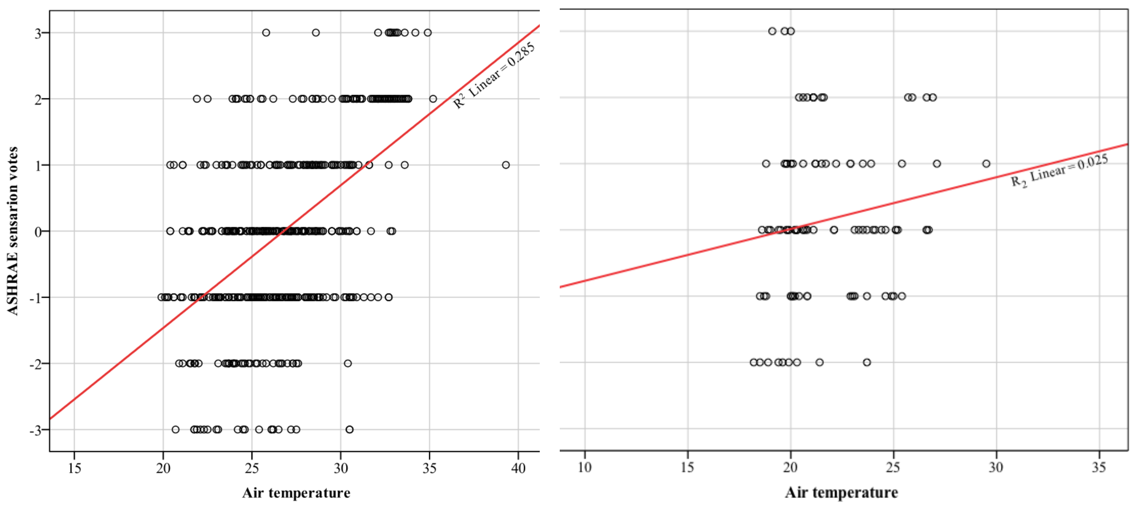


Figure 5.6 Left: a scatter diagram of sensation responses from the longitudinal survey with air temperature in the hot season; right: in the cool season.

5.3.6 *Acceptable conditions*

As an accepted method for predicting boundaries of comfort conditions and according to ISO 7730 (2008), the range of PMV (predicted mean responses) between (-1 to +1) (of sensation responses on ASHRAE seven-point scale) would result in 75% of subjects feeling satisfaction with their thermal environment. For satisfaction of 90% of subjects, the range of PMV would be between (-0.5 to +0.5). In line with this accepted method and shown in Figure 5.7 and Figure 5.8, the neutral temperature and boundaries of acceptable conditions in both seasons are presented in Table 5.21.

Table 5.21 Neutral temperature and comfort zone during both seasons

	T_n	R^2	Acceptable condition (75%)	Acceptable condition (90%)
Hot season	26.7 °C	0.285	22.7 - 29.7 °C	24.6 - 28.8 °C
Cool season	19.9 °C	0.025	15.9 - 23.9 °C	18.3 - 21.5 °C

Table 5.22 Distribution of the ASHRAE sensation scale associated with al measurements of indoor temperatures from both surveys.

ASHRAE scale			N	Mean T_a	Minimum T_a	Maximum T_a	%
Hot season	Hot	(+3)	13	32.29	25.8	34.9	2.50%
	Warm	(+2)	82	30.41	21.9	35.2	15.60%
	Slightly warm	(+1)	86	27.47	20.4	39.3	16.40%
	Neutral	(0)	149	26.14	20.4	32.9	28.40%
	Slightly cool	(-1)	132	25.75	19.9	32.7	25.10%
	Cool	(-2)	41	24.3	20.9	30.4	7.80%
	Cold	(-3)	22	24.58	20.7	30.5	4.20%
Cool season	Hot	(+3)	3	19.6	19.1	20	3.10%
	Warm	(+2)	12	22.77	20.4	26.9	12.40%
	Slightly warm	(+1)	19	22.2	18.8	29.5	19.60%
	Neutral	(0)	35	22	18.6	26.7	36.10%
	Slightly cool	(-1)	19	21.63	18.5	25.4	19.60%
	Cool	(-2)	9	19.99	18.2	23.7	9.30%
	Cold	(-3)	0	-	-	-	0%
All	Hot	(+3)	16	29.91	19.1	34.9	2.60%
	Warm	(+2)	94	29.44	20.4	35.2	15.10%
	Slightly warm	(+1)	105	26.52	18.8	39.3	16.90%
	Neutral	(0)	184	25.35	18.6	32.9	29.60%
	Slightly cool	(-1)	151	25.23	18.5	32.7	24.30%
	Cool	(-2)	50	23.52	18.2	30.4	8.00%
	Cold	(-3)	22	24.58	20.7	30.5	3.50%

Table 5.22 shows that from both seasons, 29.6% of subjects were in a neutral condition (sensation response = 0) in the air temperature range between 18.6°C – 32.9°C. However, around 70% of subjects were in comfortable conditions (-1 to +1) during the hot season in the range of 20°C and 39.3°C. Around 70% of subjects were also in a

comfortable condition experiencing temperatures in the range of 18.5°C to 29.5°C during the cool season. These results show that the proportion of subjects feeling comfortable within the response range of (-1 to +1) are higher than those predicted by the PMV model. However, 182 of the total responses, reported being warm or hot, or cool or cold, (responses of +3, +2, -2 or -3) at the time they recorded their comfort choice and around 60.4% of the 182 responses were on the warm or hot side when the mean temperature was more than 29°C.

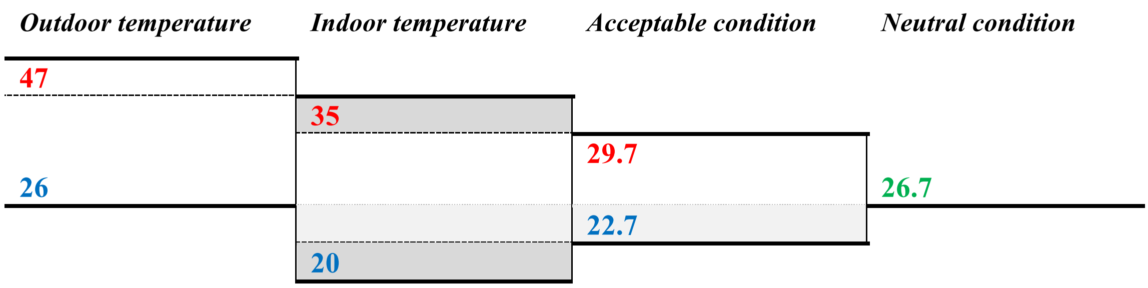


Figure 5.7 Comparison between outdoor, indoor and acceptable conditions in Dammam homes during the hot season

As shown previously in Table 5.6, the mean internal air temperature is between 21.8°C during the hot season and 26.87°C in the cool season, which is obviously due to the large daytime range and the outdoor temperatures that play a part in the indoor conditions. Figure 5.7 shows that, in the hot season, the maximum indoor temperatures, which often occurred at noon time, were well below maximum outdoor temperatures, due to the cooling strategies. However, it is also 9K higher than the minimum outdoor temperature which is close to the neutral temperature, due to the fact of poorly designed and performed homes in several cases.

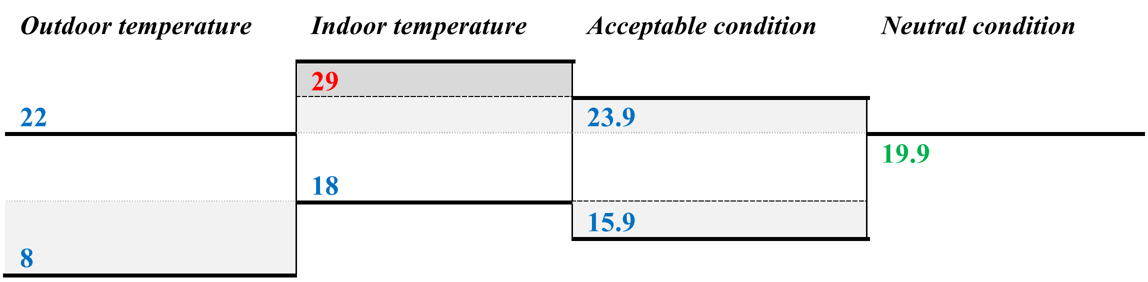


Figure 5.8 Comparison between outdoor, indoor and acceptable conditions in Dammam homes during the cool season

However, during the cool season, shown in Figure 5.8, the maximum indoor temperatures are higher than the maximum outdoor temperatures, and looking at the energy consumption chart (Figure 5.14), this shows very normal use of energy, which means that buildings are storing heat inside and people need to ventilate their dwellings. Consequently, people never choose “cold” on the ASHRAE sensation scale, as the acceptable and neutral conditions were well below the experienced indoor temperature.

5.4 Occupants' behaviour

To explore the occupants' behaviours, the questionnaire used in the study investigated the respondents' behaviours through the (ComfApp) thermal comfort survey. On average, the users stayed indoors at home for around twelve hours per day, with women spending, on average, four hours more there. When asked about their electricity bills, more than the half (57.6%) of the participants replied that during summertime they often had high bills that ranged between 500 SAR (£90) to over 1100 SAR (£200) per month. Despite the fact that the cost of a kWh of electricity delivered to the householder ranged from only 0.5 SAR (1p) for the lower energy consumers to 1.6 SAR (29p) for the highest energy consumers, around 62% reported that they considered their electricity bill was overpriced and inflated in summer and very low-priced in winter.

Table 5.23 shows the variation of all measured thermal sensations of the occupants, which have a neutral point of 0.1 during the summer. Interestingly, only 20% of the summer responses indicated that the respondents were feeling warm or hot and half of these responses were experiencing a temperature equal or above 30°C. Furthermore, around 20% of the latter responses preferred no change on the thermal preferences scale. The standard deviations of the thermal sensation in Table 5.23 provide further insights into how the perceptions of conditions in different homes vary, clearly influenced by the prevailing indoor temperatures. Moreover, looking to the means of the ASHRAE scale of 0.1 and 0.15 of summer and winter respectively, it is evident that people feel warm in both seasons and prefer to be cooler in summer and warmer in winter, which is perhaps related to their choice of adaptation.

During the longitudinal survey, in both seasons occupants were asked to indicate what environmental controls were activated during the survey voting period. The adaptations noted among the controls included the use of AC, fans, windows and doors and the heating method. Table 5.23 lists the mean and standard deviation of the control of AC and fans, as well as the opening of windows and doors, between the survey responses for all the dwellings in the hot season. Surprisingly, only 17% of the total observations recorded occupants closing the AC system off at some point during the day of the responses in the hot season. This indicates that the decision to shut down the AC system was seldom made, and in some homes, it was never turned off. However, during the informal interview and when asking people about it they said that the main reasons for shutting the AC system were that the AC was not blowing cool enough cooling air, due to an over-long operation period, or because some occupants desired to be in the warmer conditions that resulted. However, the length of operation of the mechanical systems of homes in the region may reflect the low price of electricity in Saudi Arabia at that time. As domestic prices rise it will be interesting to see if the operation period of the mechanical systems is shortened to save money. The use of fans, moreover, was limited to seven dwellings only, and the mean value of operating the fan in those dwellings varied from 0.03 to 0.50. In those dwellings, people were found to prefer to have some local air movement: one occupant reportedly preferred the cooling sensations resulting from the use of fans over those provided by activating the AC.

Table 5.23 The mean and standard deviation of all measured indoor air temperatures (T_a °C), the ASHRAE thermal sensation scale, and the preference scale, together with the proportion of activation of AC, fans, and opening of windows and doors in all the seventeen Dammam dwellings during the hot season (N: sample size; SD: standard deviation)

Dwelling #	T_a			ASHRAE		Preference		AC		Fan		Window		Door	
	N	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	34	25.8	2.7	-1.1	1.5	-0.5	0.8	0.88	0.33	0	0	0	0	0.26	0.45
2	32	27.3	2.8	-0.9	0.7	-1.3	0.9	0.91	0.30	0.03	0.18	0.03	0.18	0.53	0.51
3	21	26.8	1.8	-0.5	0.7	-1.3	0.9	1	0	0	0	0	0	0.10	0.30
4	28	28.8	2.1	0.4	1.3	-0.9	1.0	0.64	0.49	0	0	0	0	0.61	0.50
5	39	27.5	1.9	-0.1	0.9	-0.6	0.7	0.72	0.46	0	0	0	0	0.28	0.46
6	18	30.4	3.3	1.4	1	-0.6	0.6	0.50	0.51	0.50	0.51	0.11	0.32	0.39	0.50
7	36	24.1	1	-0.3	1.1	-0.4	0.6	0.89	0.32	0.06	0.23	0	0	0.28	0.45
8	25	26.8	3.3	0.4	1.2	-0.8	0.8	0.96	0.20	0.04	0.20	0	0	0.16	0.37
9	23	22.5	1.7	-0.6	1	-0.1	0.9	0.96	0.21	0	0	0	0	0.17	0.39
10	18	26.7	4.4	0.5	1	-0.6	0.5	1	0	0	0	0	0	0.33	0.49
11	17	28.6	2.9	0.4	1.2	-0.8	1.0	0.94	0.24	0.35	0.49	0	0	0.35	0.49
12	35	23.2	1.9	0.4	1.2	-0.7	1.0	0.86	0.36	0.03	0.17	0	0	0.49	0.51
13	26	28.6	2.8	-0.2	1.5	-0.7	0.8	0.77	0.43	0.23	0.43	0	0	0.62	0.50
14	27	28.2	2.3	0	1.1	-0.3	0.9	0.56	0.51	0	0	0	0	0.85	0.36
15	50	31.6	2.1	1.8	0.9	-1.8	0.6	0.92	0.27	0	0	0.04	0.20	0.58	0.50
16	22	27.7	2.7	-0.4	1.1	-1.0	1.0	0.91	0.29	0	0	0	0	0.14	0.35
17	21	27.7	2.2	-0.6	1.8	-0.2	1.0	0.76	0.44	0	0	0	0	0.52	0.51
Total	**472**	**27.2**	**3.4**	**0.1**	**1.4**	**-0.8**	**0.9**	**0.83**	**0.37**	**0.06**	**0.23**	**0.01**	**0.10**	**0.41**	**0.49**

Although all of the surveyed dwellings have operable windows, almost a nil proportion (1%) of occupants operated the windows during the day, and those were found in only three of the dwellings. In the other dwellings, windows were fully closed during the heat of the summer but opened at cooler times of the year (Table 5.24). However, interestingly, the doors which opened into uncooled indoor or semi-outdoor areas were often constantly in operation, (10% - 85% of the time) in all dwellings, with a mean value of 0.41. The decision to open internal doors to stimulate air movement around the house instead of windows to the outside was perhaps due to the preconception of the adversity of the outdoor conditions (i.e. high humidity, temperatures and dust storms) making the opening of internal doors always a more effective choice.

Table 5.24 lists the mean and standard deviation of the control of heating and fans as well as the opening of windows and doors between the survey responses for all the dwellings in the cool season. 42% of the total observations recorded occupants were using some type of heating method at some point during the day of the survey. The heating method used in homes was basically a portable source of heating, either an above ground fireplace with coal\firewood as the traditional type of heating, movable oil heaters or electric fan heaters. The majority of those who used the heating in their homes, around 51%, used electric fan heaters and around 38% and 11% used moveable oil heaters and an above ground fireplace, respectively. The main reasons for using heating were that the indoor temperature was fairly cold due to the opening of windows or doors in those dwellings. The use of fans, however, was absent in the cool season, which might be related to enough cooling coming from the openings. The operation of windows showed a significant increment compared to the hot season, with 15% of occupants operating the windows during the day or night time. In some dwellings, however, windows were fully closed and occupants preferred the opening of doors, with a mean value of 0.12. The decision to open internal doors to stimulate air movement around the house instead of windows to the outside was perhaps due to the fact that these people were used to opening the doors instead of windows in the hot season. Moreover, in two cases people neither open windows/doors nor operate fans/heating which could be related to the fact the occupants are feeling comfortable in that particular time and no need for adaptations.

Table 5.24: The mean and standard deviation of all measured indoor air temperatures (T_a °C), the ASHRAE thermal sensation scale, and the preference scale, together with the proportion of activation of the heating and fans, and opening of window and doors in all the seven Dammam dwellings during the cool season (N: sample size; SD: standard deviation)

Dwelling #		**T_a**		**ASHRAE**		**Preference**		**Heating**		**Fan**		**Window**		**Door**	
	N	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	14	20.56	2.65	-0.36	0.84	0.57	0.94	1	0	0	0	0	0	0	0
3	11	22.35	0.98	0.82	0.75	-0.36	0.67	0	0	0	0	0	0	0	0
4	10	20.43	0.72	0.60	1.35	0	1.05	0.8	0.42	0	0	0.2	0.42	0	0
5	9	19.96	0.41	1.00	1.73	1.00	0.87	0.33	0.5	0	0	0.33	0.5	0	0
12	13	19.52	0.82	-0.23	1.30	0.31	1.11	0	0	0	0	0.54	0.52	0.31	0.48
18	20	24.49	1.80	0.15	1.09	0.10	0.45	0.45	0.51	0	0	0	0	0.15	0.37
19	12	21.77	2.29	-0.50	1.31	0.75	0.87	0.25	0.45	0	0	0.08	0.29	0.33	0.49
Total	**89**	**21.60**	**2.42**	**0.15**	**1.27**	**0.31**	**0.91**	**0.42**	**0.5**	**0**	**0**	**0.15**	**0.36**	**0.12**	**0.33**

5.5 Thermal sensation in homes

It is evident from Figure 5.9 that the temperature inside these Dammam homes in the cool season, where the outdoor temperature was under 25°C, was quite moderate, as well as in the adaptive range of ASHRAE standards. On the other hand, during the hot season the indoor temperature range was between 20°C to 35°C, which is above those levels even covered by the adaptive range of acceptability, showing that people are living in a widely varying range of indoor temperatures, and that they accommodate them in the ordinary course of their day-to-day lives in their homes.

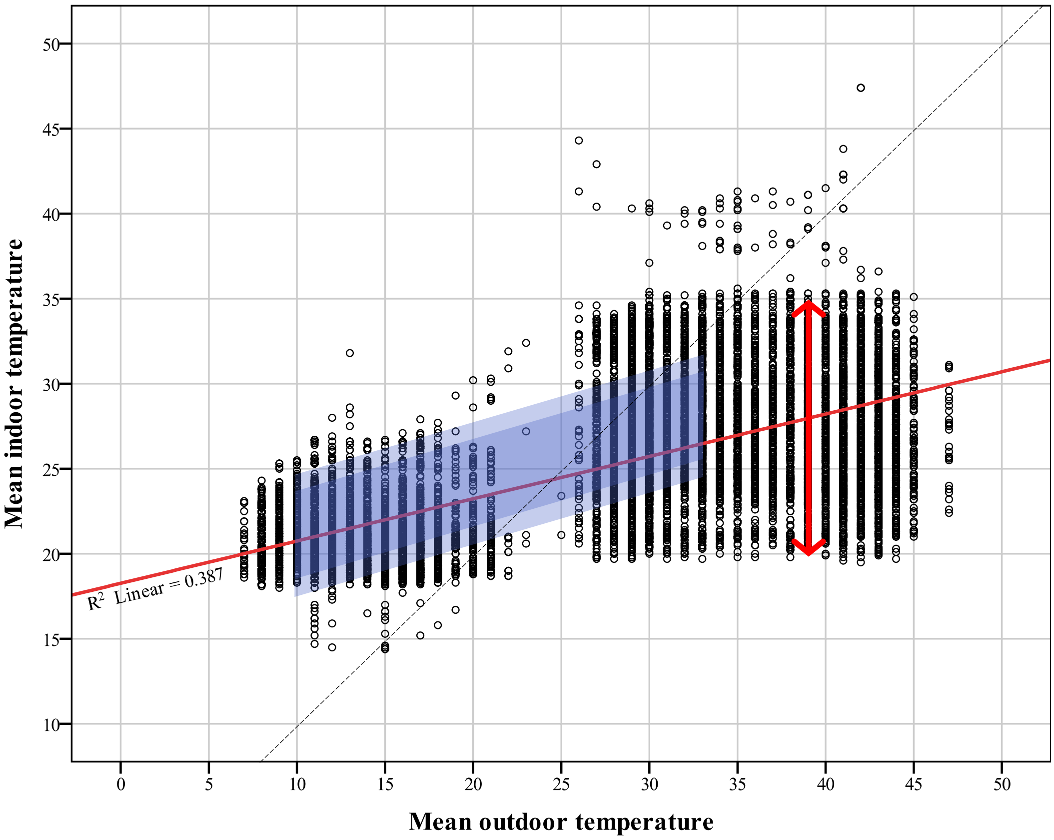


Figure 5.9 Scatter diagram of the ASHRAE adaptive standard of 80% and 90% acceptability limits of all measured physical data of the Dammam homes during both seasons, where the mean outdoor temperatures were below 25°C and 47°C for the cool season and the hot season respectively.

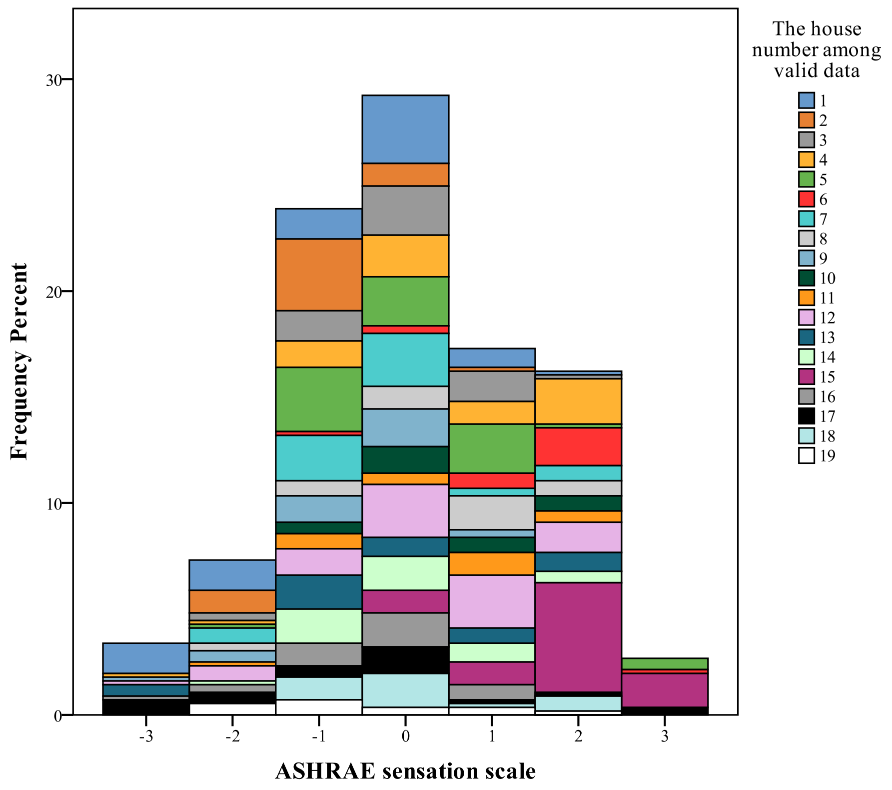


Figure 5.10 Distribution of Dammam homes according to the ASHRAE sensation responses in all seasons

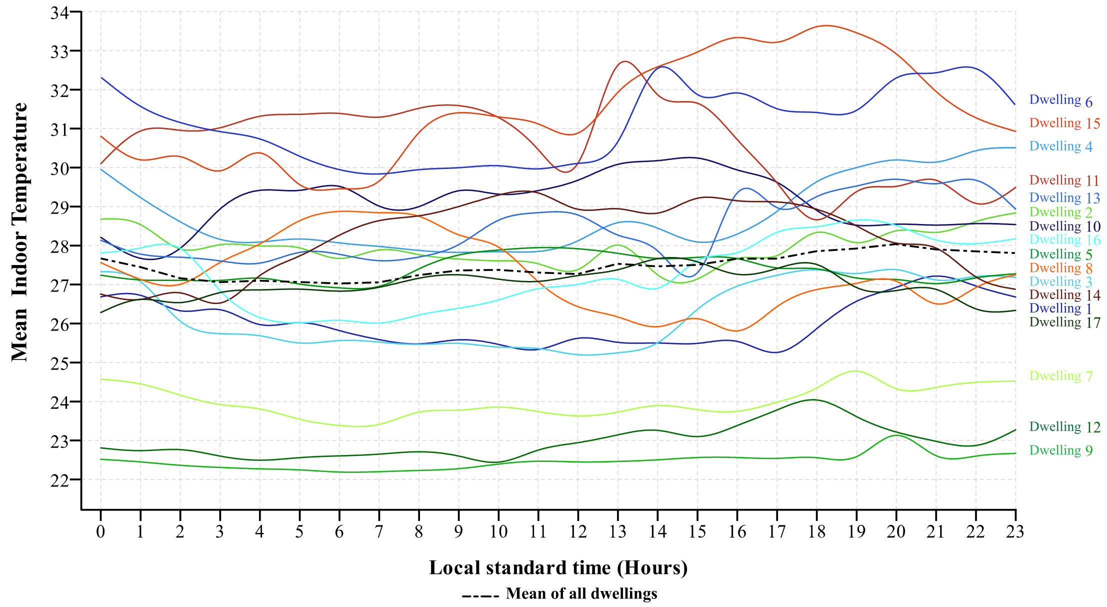


Figure 5.11 The traces of mean indoor temperature in Dammam homes during summer season

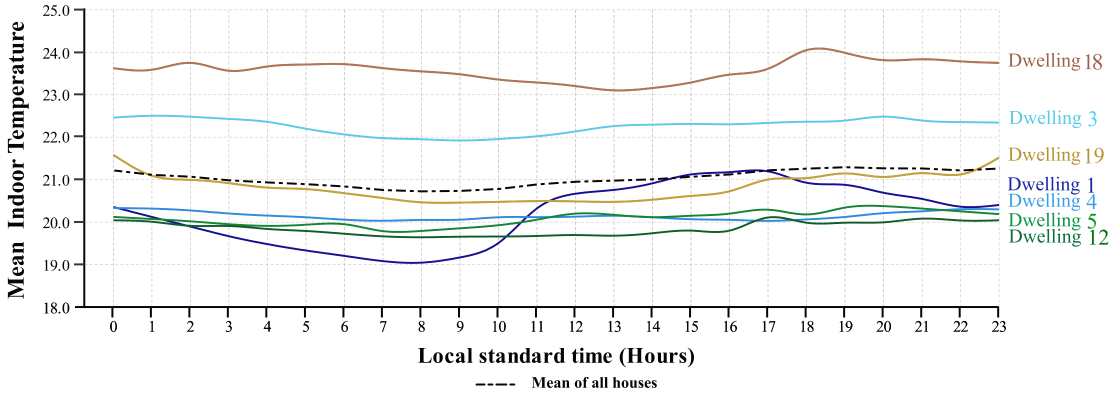


Figure 5.12 The traces of mean indoor temperature in Dammam homes during winter season

In fact, studying Figure 5.10, Figure 5.11 and Figure 5.12 shows that the studied dwellings were irregular in terms of comparison. Experienced temperature as well as calculated neutral temperature for all homes, in Table 5.25, is shown to vary significantly between dwellings, ranging from 19°C to 35°C. It is clear that some of the dwellings behave differently, as shown in Figure 5.11 and Figure 5.12 which show how the indoor temperatures behave during a period of 24 hours. Moreover, the dwellers themselves are different, and the impact of the indoor environments among them varies. The temperature performance curve for house number fifteen, for example in Figure 5.11 and the occupants ASHRAE responses in Figure 5.10, shows that these dwellers reported their thermal sensation mostly in the hot categories of the ASHRAE sensation scale. Moreover, the temperature performance curve for house number one, for example in Figure 5.12 and the occupants ASHRAE responses in Figure 5.10, shows that this dwelling is the only one who has a strong association with ambient conditions in the cool season, and the dwellers reported their thermal sensation mostly in the comfort categories of the scale. These dwellings vary in terms of thermal capacity or cooling efficiency or perhaps it is the role of the occupants in adapting. These dwellers are a fairly varied group among themselves, so the reasons behind these differences that necessarily lead to unacceptable internal temperature, leading to thermal discomfort, are sought.

Table 5.25 The differences between neutral temperatures in all homes from the simple linear regression in both seasons

Dwelling #	Slope	Intercept	R^2	T_n
1.	0.12	-3.66	0.09	31.58
2.	0.06	-2.15	0.03	35.83
3.	-0.19	4.64	0.26	24.96
4.	0.06	-1.19	0.04	19.11
5.	-0.07	1.82	0.04	27.50
6.	0.18	-4.10	0.37	22.43
7.	-0.19	4.34	0.03	22.60
8.	0.27	-6.99	0.54	25.50
9.	0.46	-10.85	0.58	23.69
10.	0.21	-5.02	0.70	24.35
11.	0.26	-7.17	0.36	27.25
12.	0.21	-4.36	0.14	20.97
13.	0.28	-8.05	0.26	29.16
14.	-0.05	1.43	0.12	28.00
15.	0.32	-8.19	0.58	25.74
16.	0.16	-4.79	0.16	30.11
17.	0.12	-3.95	0.02	32.14
18.	0.14	-3.19	0.05	23.42
19.	0.02	-0.69	0.01	31.32
All homes	**0.15**	**-3.87**	**0.41**	**25.77**

5.6 Electricity consumption

Regarding the electricity bill, 44% of participants said that they had paid more than 1000 SAR (£182) as a summer electricity bill at least once. Moreover, half of the participants said that, in comparison to the monthly income they earn, the electricity bill is expensive. Furthermore, around 61% of the respondents, claimed that the electricity prices are very high and overpriced. Around half of participants reported being not concerned about the total energy consumed in the country. Surprisingly, more than 60% of the total participants had no idea about how the increasing electricity consumption impacts as much on the environment as on the personal level, and these participants appeared to consider only the impact of cost increases. However, it is worth investigating people’s concerns after the increment of electricity prices late 2015.

Regarding the provision of the actual electricity bills’ readings and prices, the occupants of all the homes cooperated in offering a copy of the electricity bill to the researcher, except the occupants of dwelling number nineteen. According to the utility bills received from these 18 dwellings, from July 2013 to June 2014, the annual energy consumption differs between dwellings, ranging between 14907kWh to a high energy consuming dwelling with 118656 kWh. Table 5.26 illustrates a comparison between all the individual household’s electricity bill details, revealing that the average electricity consumption in this group of Dammam dwellings is up to 50142.28 kWh per annum. However, due to the dissimilarity of the dwellings, the accurate calculation should be related to the dwelling size and how much energy per square metre the dwelling is consuming. Therefore, the electricity consumption according to kWh/m^2 per year was used, which indicated that the energy consumption for the eighteen Dammam dwellings ranged from 89.3 kWh/m^2 up to 206.4 kWh/m^2, with an average of 123.33 kWh/m^2 per annum.

Table 5.26 Summary description of the electricity bills from July 2013 to June 2014 collected from 18 studied dwellings

Dwelling#	**Mean monthly bill** (SAR)	**Mean monthly consumption** (kWh)	**Maximum bill per year** (SAR)	**Maximum consumption** (kWh)	**Annual bill** (SAR)	**Annual consumption** (kWh)	**Annual consumption** (kWh/m^2)
1	81	1267	134	2071	970	15207	95.04
2	222	2832	618	6927	2667	33988	97.11
3	434	4695	1007	9508	5204	56339	125.20
4	374	4190	986	9440	4494	50280	111.73
5	1202	8613	5469	30640	14426	103360	108.80
6	506	5207	1131	10160	6075	62480	89.26
7	629	5933	2532	19584	7547	71194	118.66
8	152	2487	304	4539	1829	29847	165.82
9	110	1590	204	2528	1319	19079	90.85
10	81	1353	182	3019	974	16230	101.44
11	1048	9888	2532	19584	12578	118656	148.32
12	102	1242	226	2460	1225	14907	106.48
13	617	6019	1543	11975	7407	72233	206.38
14	190	2622	463	5781	2275	31462	125.85
15	698	6387	1725	12480	8374	76640	201.68
16	167	2516	386	5588	2005	30197	104.13
17	312	3795	673	7024	3749	45535	101.19
18	396	4577	1145	12395	4754	54927	122.06
Total	**407**	**4179**	**-**	**-**	**4882**	**50142.28**	**123.33**

Figure 5.13 illustrates the average annual energy consumption by kWh/m^2 and the operational cost of each square meter, along with the estimated operational cost of each home at the present rates. The operational cost of the studied homes is meant to represent the cost of obtaining the thermal comfort level, which includes only the cost of electricity bills, in that approximately 70% (MOWE, 2012) of the electricity is consumed by the cooling system, and the cost of the AC system maintenance per annum in each home. In this study, the mean annual consumption of all dwellings of 123.33 kWh/m^2 with an about 5 kWh/m^2 as a regular consumption every month, indicates that the cooling demand is approximately 50% of the total energy consumption. As the cost of operating the cooling system depends on the number of cooled rooms in the individual

home as well as the efficiency of the cooling system, the price of the annual electricity bill ranged between 970 SAR (£177) and 14,425 SAR (£2,622) and adding the cost of the maintenance without the cost of the failure of parts, the operational cost ranges between 2,574 SAR (£468) to 19,825 SAR (£3,604). However, with the new electricity prices that will possibly affect around half of the studied dwellings, precisely almost all low performance dwellings, the annual operational cost could reach around 28,500 SAR (£5,180), without the cost of the failure of the system's parts.

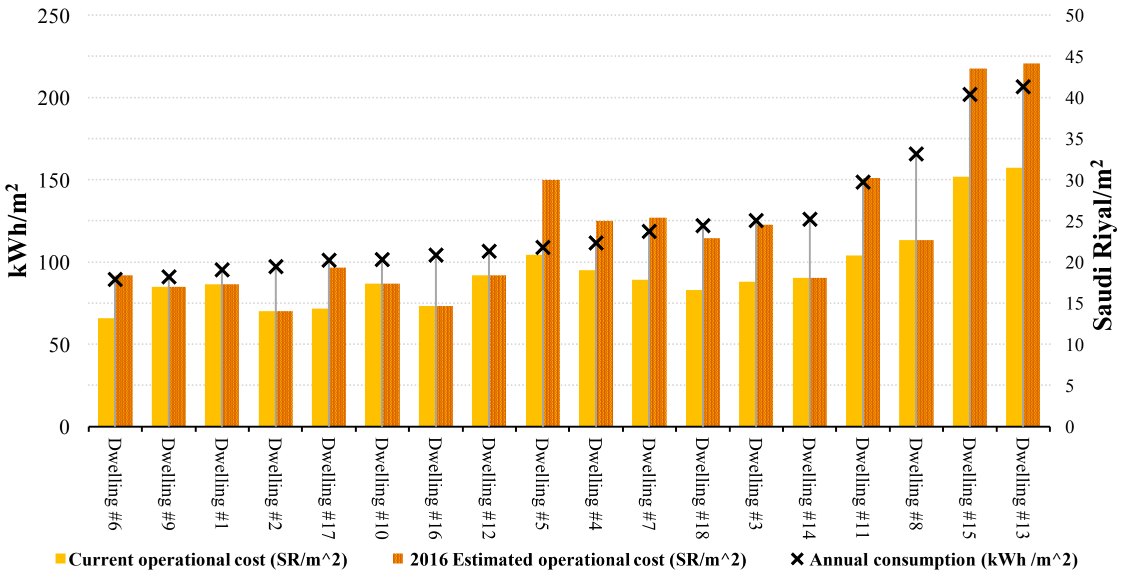


Figure 5.13 The annual electricity consumption of each of eighteen dwellings, per square metre, alongside its operational cost and the estimation of cost since late 2015 in Saudi Riyals (1SAR=£0.18), redistributing the homes' sequence in ascending order by kWh/m^2.

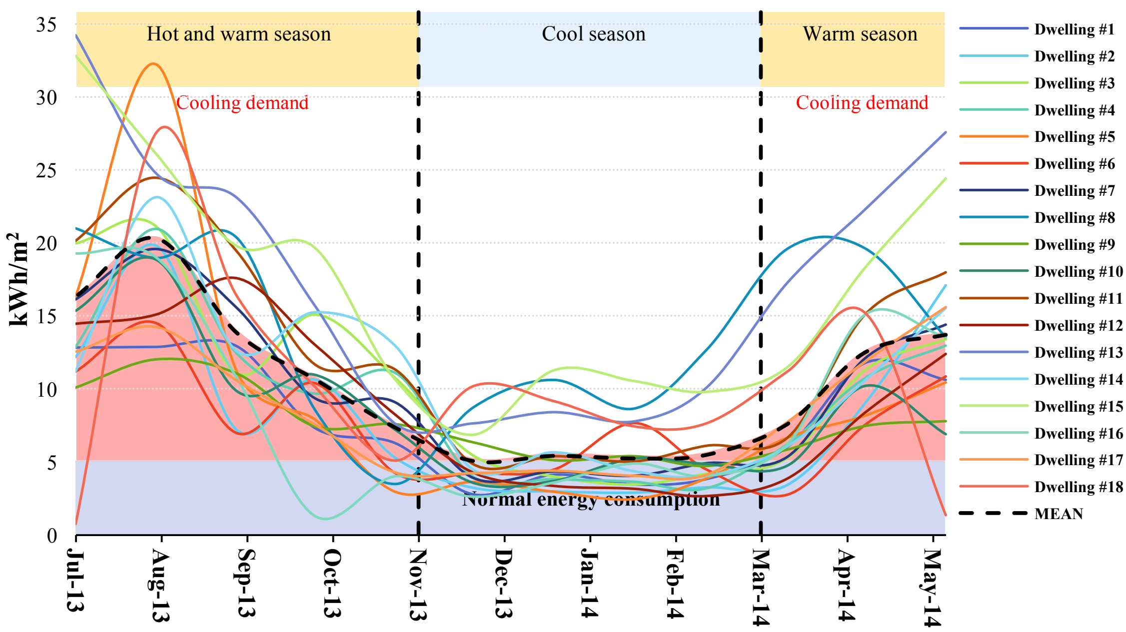


Figure 5.14 The electricity consumption in kWh/m^2 per month for the eighteen studied Dammam dwellings, with the mean monthly kWh/m^2 from July 2013 till May 2014

It can be seen also in Figure 5.13 that some dwellings, for example thirteen and fifteen, have reached a very high total energy consumption and relatively high operational cost among the homes in this study. Therefore, a further analysis looking into individual homes' design characteristics and the occupants' thermal comfort and behaviours is sought. The electricity bills showed a type of consistent energy consumption across the utilised sample. It is evident from Figure 5.14 that the time of the year when people are consuming the most energy is from March until November, whereas during the cool season months, the mean consumption in kWh/m^2 in the studied dwellings was as low as 5.2 kWh/m^2 per month. Although this amount of energy is expected to produce hot water in the dwellings and in a few cases is for heating reasons, it was not possible to assess the dwellings with high energy consumption during the cool season, due to lack of collaboration with those dwelling's occupants.

5.7 Summary

The main points of this Chapter are:

1. The surveys described in this chapter were done during two seasons (hot and cool) in the city of Dammam and yielded 622 sets of data. Around eighty percent of the samples were obtained in the hot season.
2. Air temperature, relative humidity, clothing insulation and metabolic rates were recorded simultaneously with the time of respondents' responses.
3. The pattern of sensation responses showed that around 75% of respondents reported sensation within one of the three central categories on the seven-point ASHRAE scale.
4. Limited differences in the mean clothing values were reported as 0.42 during the hot season and 0.49 during the cool season.
5. People in the cool period reported undertaking fewer activities than in the warm period.
6. The mean sensation responses were 0.02 in the warm period and 0.15 in the cool period. The neutral temperature was 26.7°C in the hot season and 20°C in the cool season.
7. The range of indoor temperatures recorded during the cool period fell almost within the adaptive comfort standard limits, while in the hot period they fell well out of the adaptive limits, with a range of between 20°C to 35°C, and yet these were considered as ordinary liveable conditions.

8. In both seasons, there was a significant difference in neutral temperatures within the nineteen sample dwellings, ranging between 19°C and 35°C.

Based on these findings, the causes and effects of these differences in the data reported between homes will be explored in the next chapter. In Chapter six, conclusions are drawn from these studies on the development of principles that can make homes in Dammam more thermally comfortable.

CHAPTER SIX: DIFFERENCES BETWEEN DWELLINGS

"When architect design houses with large windows to pull the daylight into the house, curtains come to play a big role in the interior architecture"

Arne Jacobsen

6.1 Introduction

Building on the conclusion of the findings and analysis chapter, the aim of this chapter is to explore the differences between different dwellings, particularly in the hot season where these differences seem more critical than in winter. For the full cohort of dwellings, firstly, individual buildings are classified by performance, then the more noteworthy dwellings are selected for in-depth analysis. The analysis of each selected dwelling begins with a general description of the characteristics, occupants' behaviour, and energy consumption of each dwelling. The first section of this analysis highlights the factors that characterise the dwelling, including its location, orientation, age, size, material, insulation and the type of mechanical ventilation used. The second section presents the demographic information regarding the dwellers and the available data on their daily behaviour. The final section summarises the dwellings' energy bill over the year and the energy and operational cost per square metre of each dwelling.

6.2 Distribution and selection of dwellings

The performance of the indoor temperatures in Dammam's dwellings during the hot season, shown in Figure 5.11, shows the seventeen dwellings fall into three clear groups, as shown in Figure 6.1. The classification of these three groups was derived according to how the internal temperature of each dwelling performed in terms of the range of their temperature fluctuations from the beginning of the day until midnight. In the first group (Cluster A), dwellings performed steadily within a very slight range of temperature of less than two degrees Celsius during the twenty-four hours. In the second group (Cluster B) the dwellings temperature changes fluctuated within three degrees Celsius, also demonstrating a noticeable increase in temperature during the afternoon. The last group (Cluster C) are those where the temperature fluctuated very dramatically, and/or the average temperature varied by more than three degrees Celsius. Table 6.1 shows the thermal profiles of the dwellings divided into the three clusters A, B and C, which will be analysed in detail in this chapter.

In order to select the most significant case from each cluster, Figure 6.2 provides a clear indication of the differences of the householders' responses to the ASHRAE sensation scale during the hot season. The results of the sensation responses, along with the three types of dwellings' performance classification, reveals some critical and interesting data about certain dwellings that demand deeper study. It is also worth looking closely at some of the cases that might be considered as more ideal, in that their temperature data are closer to reasonable mean temperatures, with normal distribution of the sensation votes. Using these criteria, therefore, dwellings numbers five, nine and twelve from Cluster A; dwellings number one, three, six and thirteen from Cluster B; and dwellings number eight, eleven and fifteen from Cluster C were chosen for further investigation, see Table 6.1. The analyses primarily address the hot season, with a brief mention of the available data during the cool season. The following sections will study these clusters on a case by case basis.

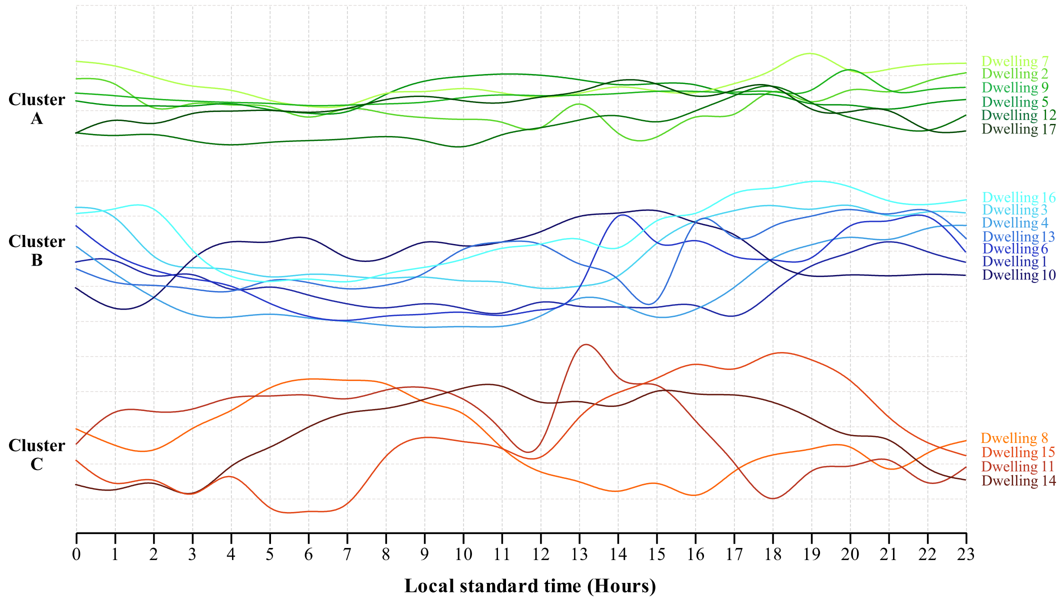


Figure 6.1 The classification of dwellings into three groups, based on the performance of the internal temperatures

Table 6.1 Thermal profiles from dwellings in clusters A, B and C, with the dwellings chosen to be analysed in more detail in this chapter underlined.

Cluster	Characteristic	Dwelling #	Type	Season participated
Cluster A	$\Delta T_a < 2K$	2	Apartment	Summer
		<u>5</u>	<u>House</u>	<u>Summer /Winter</u>
		7	House	Summer
		<u>9</u>	<u>Apartment</u>	<u>Summer</u>
		<u>12</u>	<u>Apartment</u>	<u>Summer / Winter</u>
		17	House	Summer
		18	House	Winter
		19	House	Winter
Cluster B	$2K < \Delta T_a < 3K$	<u>1</u>	<u>Apartment</u>	<u>Summer / Winter</u>
		<u>3</u>	<u>House</u>	<u>Summer / Winter</u>
		4	House	Summer / Winter
		<u>6</u>	<u>House</u>	<u>Summer</u>
		10	Apartment	Summer
		<u>13</u>	<u>House</u>	<u>Summer</u>
		16	Apartment	Summer
Cluster C	$\Delta T_a > 3K$	<u>8</u>	<u>Apartment</u>	<u>Summer</u>
		<u>11</u>	<u>House</u>	<u>Summer</u>
		14	House	Summer
		<u>15</u>	<u>House</u>	<u>Summer</u>

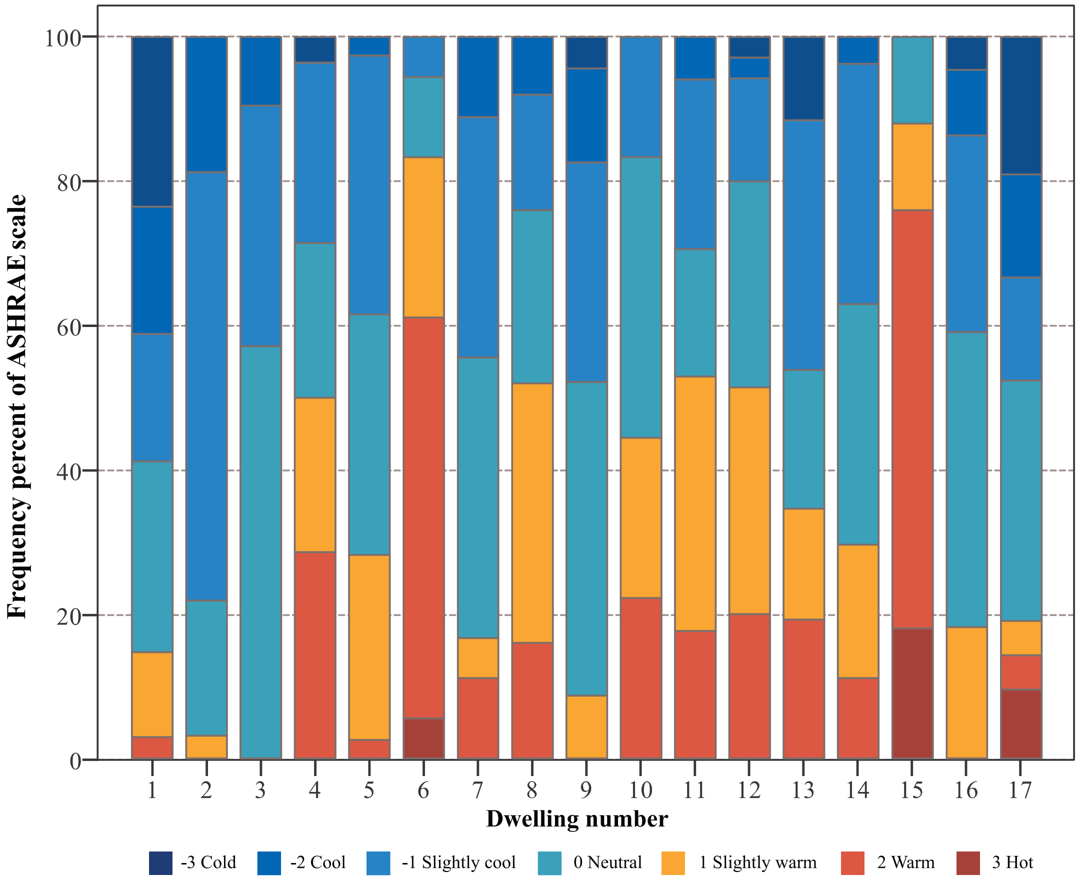


Figure 6.2 The proportion of ASHRAE sensation votes as distributed in each of the selected Dammam dwellings in the hot season; a neutral response means the subjects do not feel warm in the hot season.

6.3 Cluster A

6.3.1 *Dwelling #5*

This house is located in the North of the Rakah neighbourhood ~3000m away from the seashore to the east. The size of the house is ~ 950m^2, with a southeast orientation and it is located on the street corner. This villa, shown in Figure 6.3, has two storeys and was constructed after 2000. It was built of concrete blocks and coated with natural stone on the east and south elevations, with beige colour plaster on the north and west elevations. It was constructed with a high-quality roof and external wall insulation (25cm thickness of polystyrene sandwiched blocks for external walls and 10cm hollow concrete blocks for the internal wall), with single glazed windows and with 11.87% window to wall ratio. The type of mechanical ventilation operated in the house is a central HVAC system with several split units in some parts of the house and all rooms ceilings are covered by suspended ceilings concealing the ducts, piping and HVAC system. The mechanical systems are not maintained very often, being cleaned once or twice a year.

Being in a large lot, the owner had originally been planting the surroundings of the house, but he claimed that it consumed too much money, effort and lots of water. Thus they decided to take out all the plants and use the setback spaces for some further extensions to provide additional storage and also an outdoor dirty kitchen.

The resident family consisted of twelve adults and six children, including the father's mother, the father and the mother, five sons, two of whom are married, with six grand-children and two house maids who live on the premises. This family is classified within the high-income household group in this study, as the annual income is between 220 to 440 thousand SAR (£40-80 thousand per year). The subjects involved in the study were the house owner and his wife. They were in their sixties and both overweight. As the husband worked as a legal counsel at several companies, he spent less than ten hours a day in the house, while his wife was in the house most of the day as a house-wife. They both preferred to spend most of their time in the bedroom section, as it was quieter than the rest of the home. However, they were both dissatisfied with the design of the house as it was not any longer big enough for the family, and also the house needed a complete renovation.

As the family occupied both floors, the indoor physical measurements were collected from the living room (southeast) on the ground floor and the bedroom (east, southeast) on the upper floor. It is clear from Figure 6.4 that in terms of thermal performance, the house performed fairly well, with just above mean indoor temperatures found for the Dammam dwellings in this research. Moreover, Figure 6.5 shows in detail how the mechanical ventilation has significant control over the indoor environment. When operating the HVAC system all the time, at a specific thermostat setting, as in the bedroom, it shows that the outside condition has little impact on the indoor temperature. The bedroom temperature was fairly stable between 24.8 ºC and 27.4ºC, and the relative humidity ranged between 58% and 68%, which was considerably higher than the outdoor condition, due to the occupant's activity, as well as the opening to a fairly large bathroom. The performance in the living room was quite different, however, as the central HVAC system was only operated when the room was occupied, which seemed to be from 3pm until 10pm, and the temperature remained stable until the sunrise in the morning. It appears that the temperature in the living room fluctuated between 24ºC to

33ºC. The relative humidity, however, also appeared to be higher than the outdoor condition, fluctuating between 45% and 70%. This high range of humidity could be related to the design of the living room, which opens to the hall and other rooms on the ground floor and also the opening of doors, as well as more people using the living room. Moreover, this amount of humidity had caused some problems in previous years, as the owner said, the insulation had damaged the internal walls, due to the saturation caused by the condensation; these had been renovated later with condensation-resistant materials. Another point is that the owner of the dwelling blinded the middle opening in the living room and the master bedroom by cement permanently, as they said that "*it helped these rooms to keep the internal conditions more stable*".

Figure 6.3 The design layout of dwelling #5

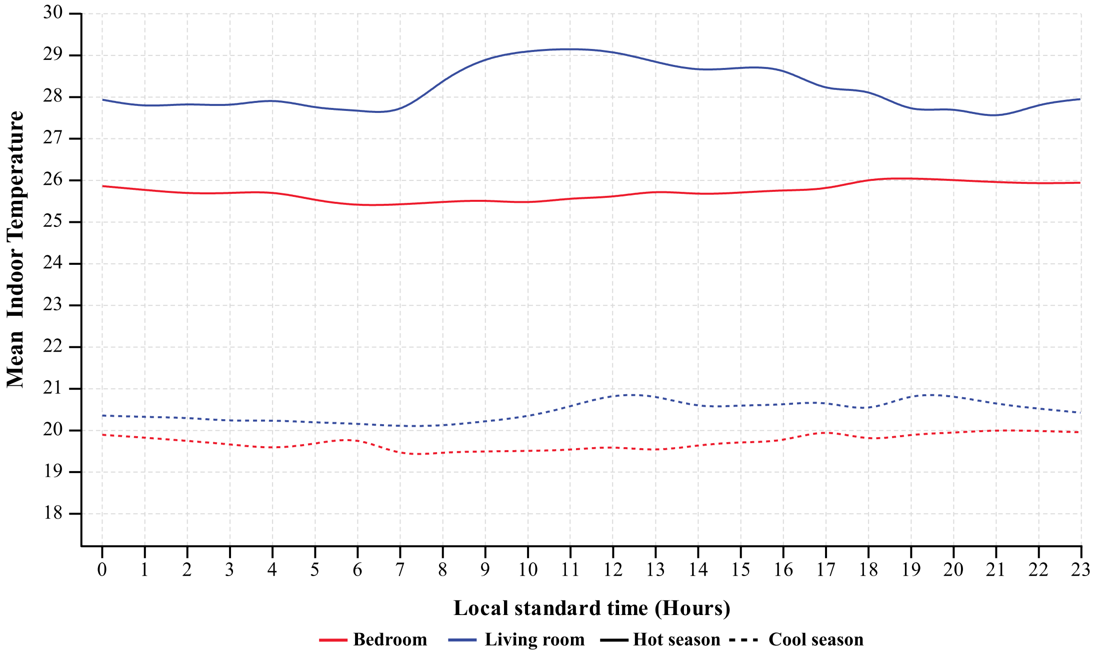


Figure 6.4 The average performance of the indoor temperature of the bedroom and living room of dwelling #5 in both seasons within a 24-hour time-series.

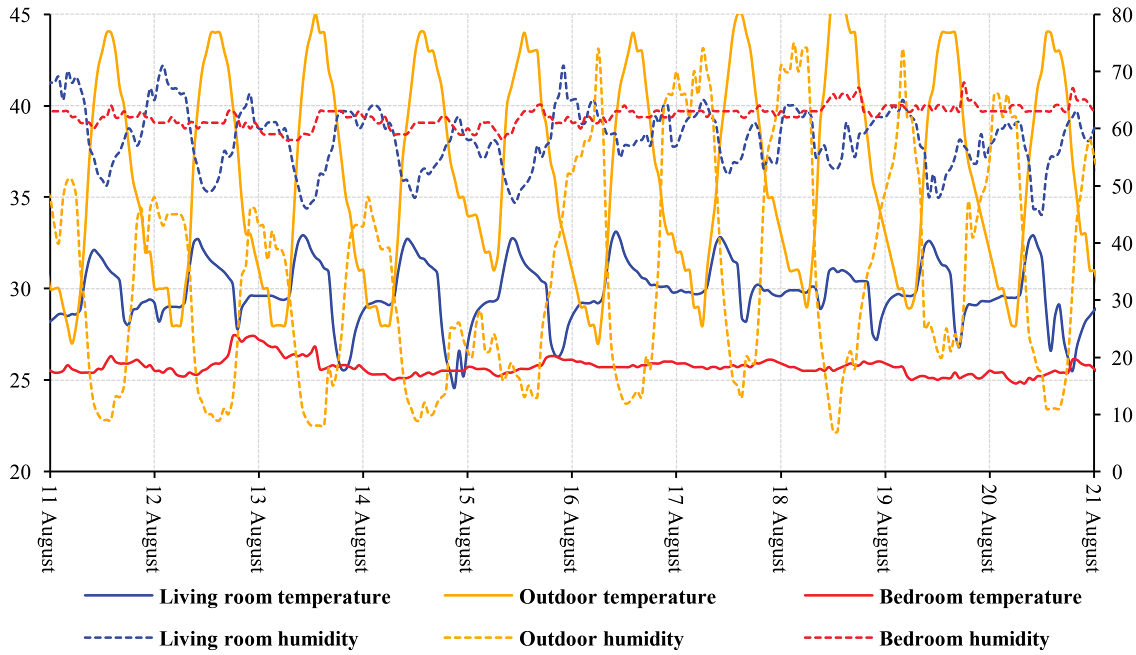


Figure 6.5 Plot of physical measurements of bedroom and living room of dwelling #5 along with outdoor conditions during the study period in the hot season.

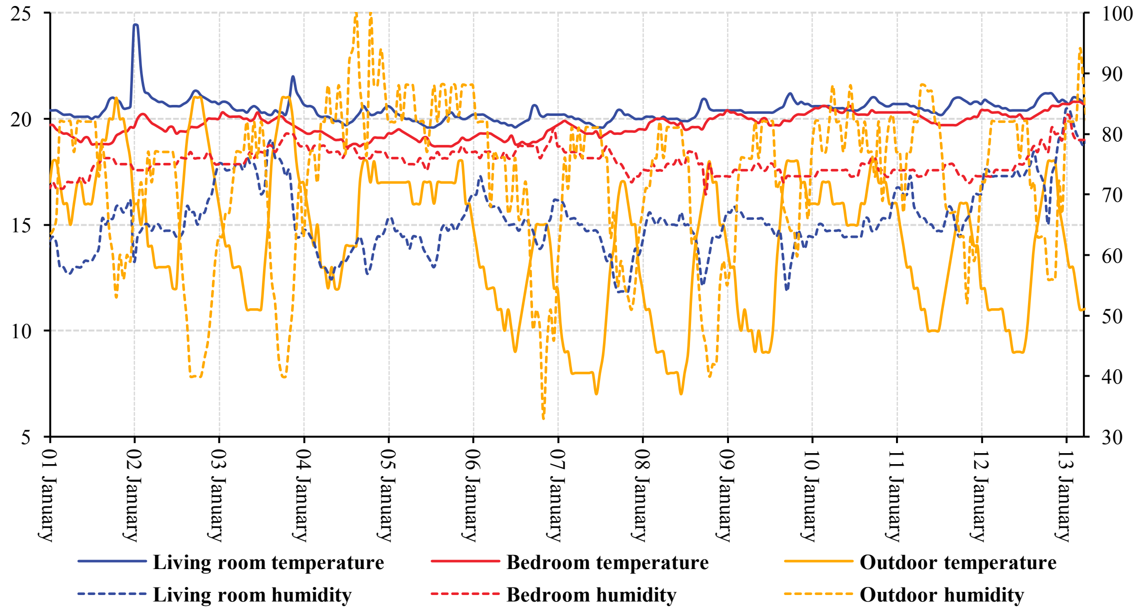


Figure 6.6 Plot of physical measurements of bedroom and living room of dwelling #5 along with outdoor conditions during the study period in the cool season.

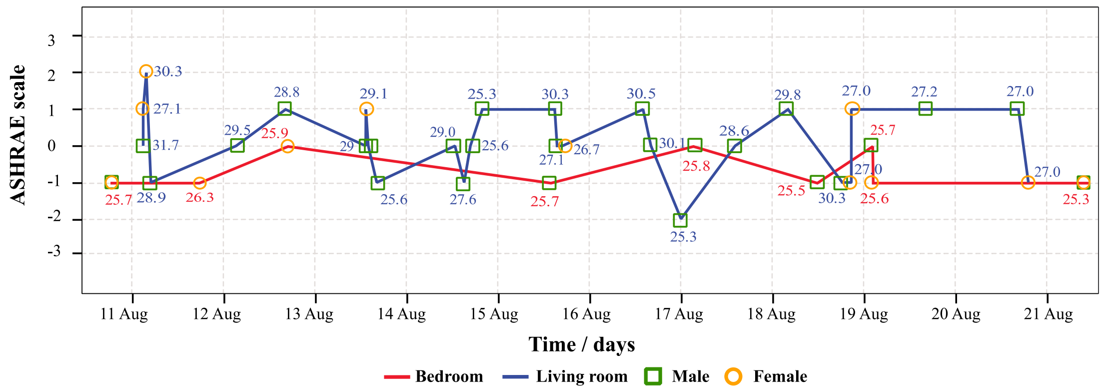


Figure 6.7 Scatter of gender and place of ASHRAE sensation votes in a multiple time-series with annotation of indoor temperature in dwelling #5 during the hot season.

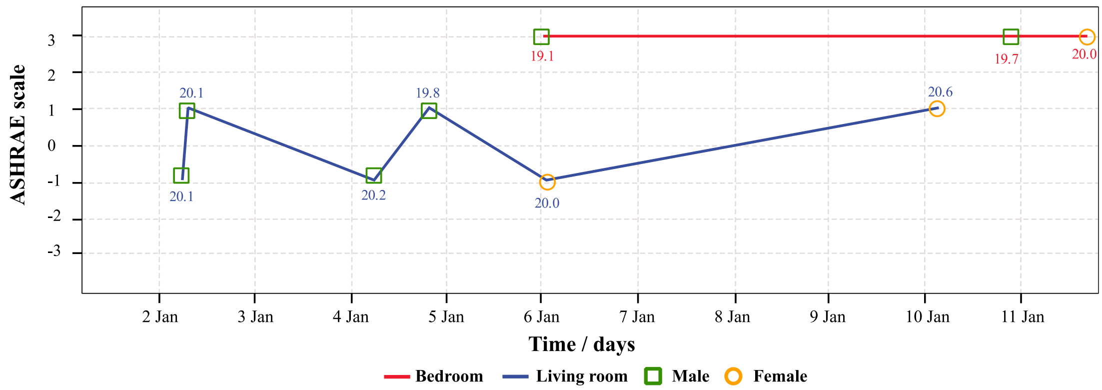


Figure 6.8 Scatter by gender and place of ASHRAE sensation votes in a multiple time-series with annotation of indoor temperature in dwelling #5 during the cool season.

Regarding the ASHRAE sensation scale, the householder's responses were almost neutral and slightly cool. Figure 6.7 and Figure 6.8 show how the occupants perceived the temperature in different seasons. In the bedroom, for example, the occupants seemed to be satisfied with the operation of the central HVAC system, as the temperatures were constant and they never voted slightly warm or above in the hot season. However, they only voted hot in the cool season, at a temperature of 20ºC and below. Those choices could be related to the south-east orientation of the bedroom as well as to the interior design, as it had carpet flooring, and a heavy type of curtains over the windows. Furthermore, the cool season sensation votes were contributed at midnight, and may have related to the amount of air flow, as the curtains were closed. Moreover, the occupants stated that they were wearing winter pyjamas which also might have compounded the effect on the sensation vote. On the other hand, the maximum of 27.4ºC with the peak of 68% RH increases the risk for excess dust mite populations, with 65% a critical threshold at that temperature.

In the living room, however, the sensation votes fluctuated in the comfortable range (slightly warm, neutral and slightly cool). What was interesting was that they choose neutral and slightly cool at temperatures of 30ºC. This happened once on the 18th of August, and during the informal interview the male subject stated that he switched the AC on after a meal and sat on purpose directly under the airflow, so that he felt slightly cool, and he preferred no change at that moment when he was responding to the survey, where the room temperature gradually decreased afterwards. In winter, the sensation votes also fluctuated, lying within the comfortable choice range.

In terms of temperature preferences and behaviour, the occupants generally preferred to have more cooling in both rooms, and the responses were mainly from the male occupant, who was regularly outside the house during the day and some of the evening, so the outdoor conditions influenced him, as he said. Interestingly, the occupants never opened the windows during the hot season and around 30% of their total responses included the operation of the internal door into uncooled indoor space. The situation in the cool season, however, was different, as around 33% of their responses included the operation of windows and none of doors. This behaviour might be due to the preconception of the outdoor conditions that makes the opening of internal doors in summer and windows in winter always a more effective choice.

With regards to the amount of electricity consumption, the householder stated that they occupied and cooled almost all rooms during summer, as some of their relatives visited them during the summer holidays. They stated in the general questionnaire that they started to operate the cooling system from April and did so until November during daytime, and from May to October during the night-time. During August 2013, when the study was undertaken, the energy bill was 5469.1 SAR (£908) for a total electricity consumption of 30640 kW/h for the month (see Figure 6.9). This amount of both cost and energy was very high compared to the other months in the hot season, as well as the bill in August 2014. The total payment of the energy bill for the whole of 2013 was 14,425 SAR (£2622) for 103360 kWh electricity consumption. Consequently, the amount of energy consumed in this house was around 109 kWh/m^2 per annum and the share per person was ~5742 kWh per capita per annum. However, with the new electricity tariff, the annual electricity bill could reach 23,080.75 SAR (£4,196.5) per annum.

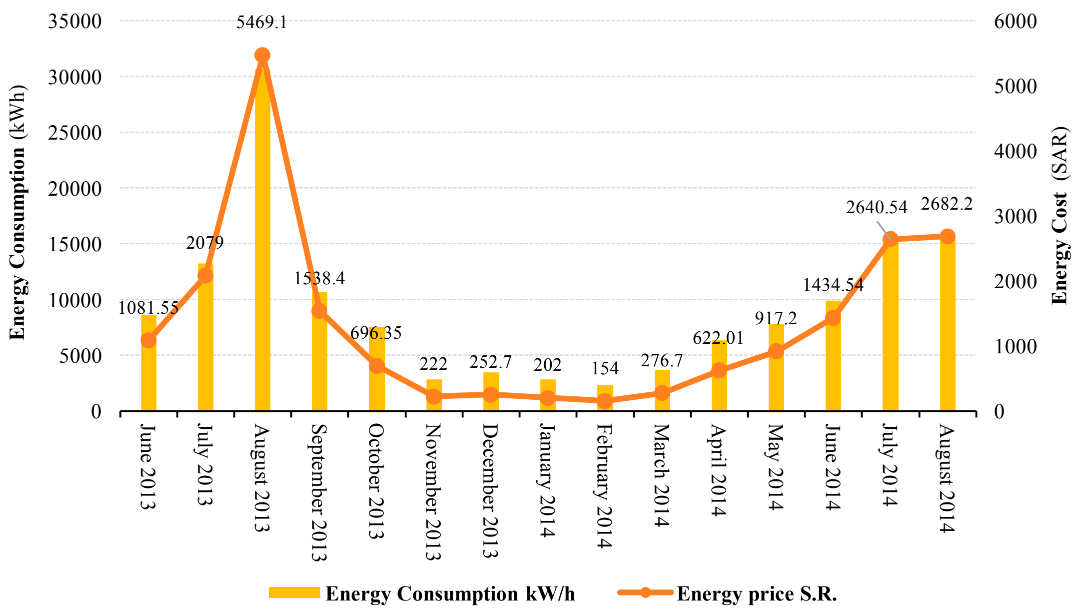


Figure 6.9 Illustration of an example of the energy consumption of dwelling #5, along with the cost of the electricity bill.

Furthermore, as 70% of the cost of the electricity bill is subject to the cooling demand, the operational cost of the cooling system for the twelve rooms in this house included the cost of the electricity bill and the cost of the AC system maintenance, which is around 3,600 SAR (£654.6) for a single maintenance visit, which is around 19,825 SAR (£3,604) per annum. However, with the new electricity tariff, the annual operational cost could reach up to 28,480.9 SAR (£5,178.3), without the cost of replacement of any faulty parts during maintenance.

6.3.2 *Dwelling #9*

This dwelling is located in the North of Khobar neighbourhood, ~700m away from the seashore to the east. The size of the apartment is 210m^2, northeast oriented and situated on the first floor of a three storey apartment building constructed after 2000. Figure 6.10 shows the design layout of the dwelling, which was built with white lightweight concrete blocks, with natural granite blocks on the street elevations (north and east), with beige coloured plaster on the other facing elevations. It was constructed with high-quality roof and external wall insulation (25cm thickness of polystyrene sandwiched blocks for external walls and 10cm hollow concrete blocks for the internal wall), and double-glazed windows and with 7.71% window to wall ratio. The ceiling is covered by a suspended ceiling concealing the ducts as full building mechanical ventilation is supplied by a central HVAC system and regularly maintained over the year.

The family who live in this apartment consists of a father and a mother with two children and a house-maid. This family is classified within the high-income household group in this study, with an annual income between 220 to 440 thousand SAR (£40-80 thousand). The subjects involved in the study were the house owner and his wife. The husband was in his thirties and with a healthy weight, whereas his wife was in her twenties and slightly overweight. As the husband works at ARAMCO oil company as a safety engineer, he spends most of the day at work, while his wife stayed in the flat as a housewife. Although they were both satisfied with the design of the flat, the male occupant preferred to spend most of the home time in the bedroom as it's quieter. However, the female liked to be in the living room during the day while the children were at school and preferred the bedroom after dinner when the children were in bed. The householders were fairly satisfied with the flat design, apart from the huge and rarely used guest room, which they would prefer to add to the living room.

The indoor physical measurements were collected from the living room (middle of the flat) and the bedroom (northeast). It is evident from Figure 6.11 that the thermal performance in the flat was controlled very well by the central HVAC system. Figure 6.12 shows in detail how the indoor environment of the apartment behaved when operating the central HVAC system all the time. It clearly shows that the outside conditions had no impact on the indoor temperature, which is a proof of the advantage of insulation and the orientation of the apartment. Being on the east side of the building, a distinctive feature of the flat was that it had no west-facing windows, and only one window on the south side, so avoiding ingress of the worst of the summer afternoon heat. As the flat temperature was set to 22ºC, it is obvious from Figure 6.12 that the bedroom is cooler than the living room. The bedroom runs at around two degrees cooler than the living room with more humidity instability. It is good to mention here that the living room benefits from the buffering of the kitchen although it has little source of daylight. This outcome might be related to the location of the bedroom, facing north, with the least sun exposure within the flat. The humidity in the bedroom fluctuated between 60% and 70% relative humidity, while in the lounge it was generally above 70% relative humidity. This is because the living room is open to the kitchen, where cooking takes place, and other parts of the flat.

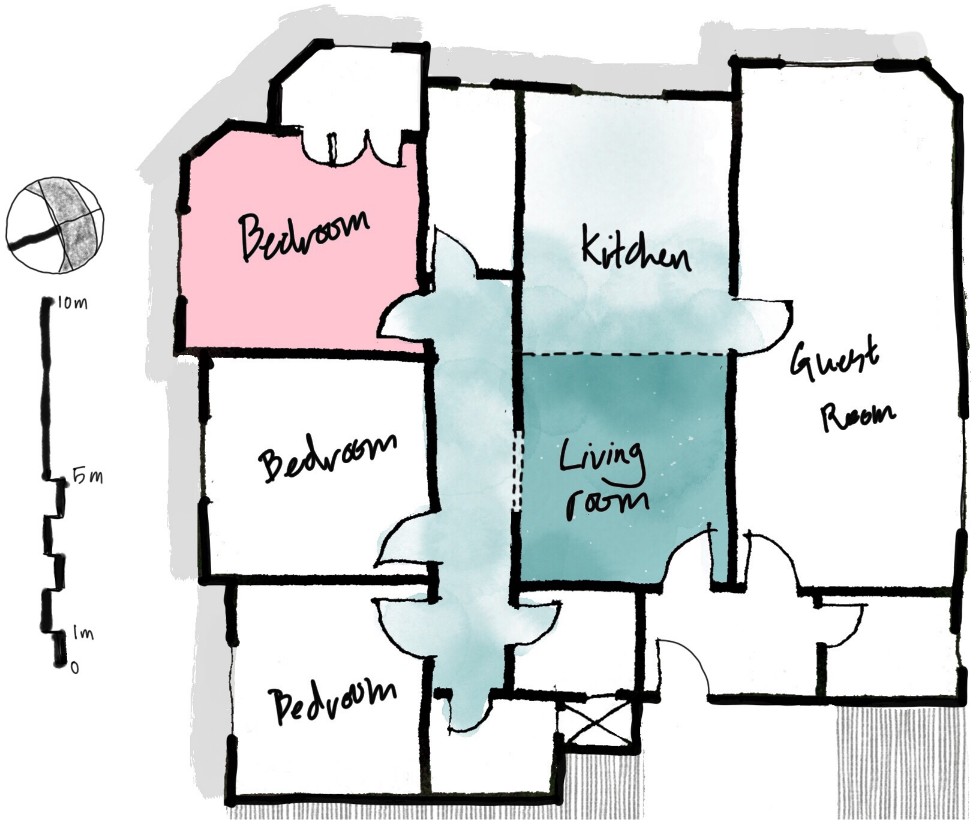


Figure 6.10 the design layout of dwelling #9.

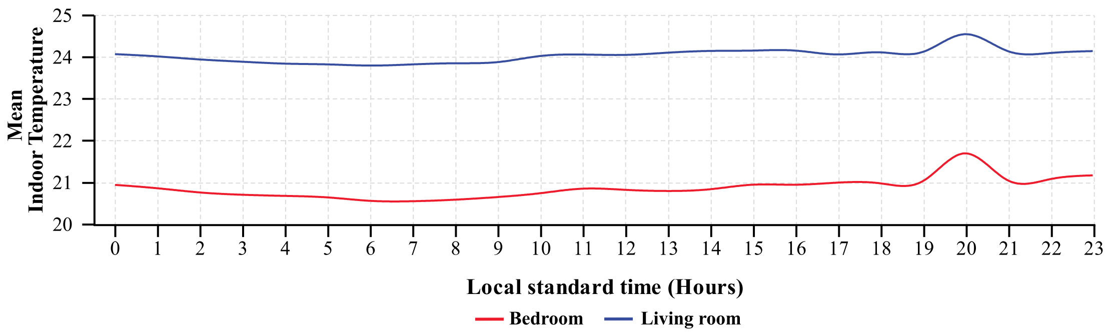


Figure 6.11 A 24-hour time-series of the average indoor temperature performance in the bedroom and living room of dwelling #9 during the hot season.

The clear differences between the temperature measured, humidity recorded, and thermal sensation and preferences could be related to the design of the interior spaces as well as the function of each room. The bedroom faces north, with no direct solar radiation in the summer, while the living room is located in the middle of the apartment opening to the kitchen, as well as to the corridor leading to the bedrooms and toilets. The bedroom always has less activity taking place than other spaces, where more functions and activities occur, including cooking, watching TV and fitness exercises.

Regarding the ASHRAE sensation scale, the householders responded differently depending on the room occupied. Figure 6.13 shows that the occupants felt cool and slightly cool in the bedroom at a temperature between 19 ºC to 21ºC, with several preferences recorded as preferring to be a bit warmer. Those choices could be related to the location of the bedroom within the flat, as well as the occupants clothing rate of 0.23 *clo* in the bedroom, with such lower temperatures. In the living room, however, they voted neutral almost all the time.

Regarding the adaptation to the internal conditions, most of the preferences votes were not to change the indoor temperature and the recorded desire to be warmer in the bedroom was stronger than a desire to be cooler in the living room. The adaptations related to these preferences were never opening windows and 17% of their total responses included the opening of the internal door into the uncooled indoor space.

Regarding the amount of the electricity consumption, the householders stated that they operated the central HVAC system all the time from March to November. During August 2013 when the study was undertaken, , the energy bill was 204.3 SAR (£37) with a total of ~2527.8 kW/h electricity consumption (see Figure 6.14). The total energy bill in 2013 was ~1318.8 SAR (£240) for 19078.8 kW/h electricity consumption, and due to the low monthly consumption there will be no change to the future cost under the new electricity tariff. Thus, the amount of energy used in this dwelling was ~90.9 kWh/m^2 per annum and the share per person was ~3815.8 kWh per capita per annum.

Furthermore, as 70% of the cost of the electricity bill is subject to the cooling demand, the operational cost of the cooling system for the five cooled rooms in this flat included the cost of the electricity bill and the cost of the AC system maintenance, which was around 1,500 SAR (£272.7) for a single maintenance visit, was around 3,568.96 SAR (£648.9) per annum and there are no increment to the operational cost after the new prices.

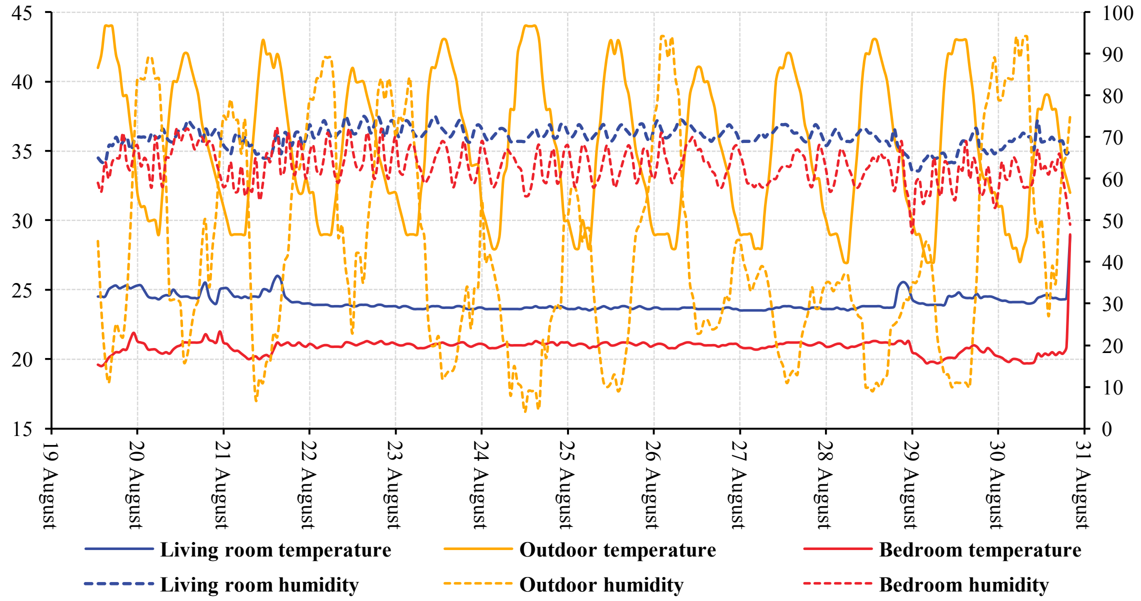


Figure 6.12 Plot of physical measurements of bedroom and living room of dwelling #9 along with outdoor conditions, during the study period in the hot season.

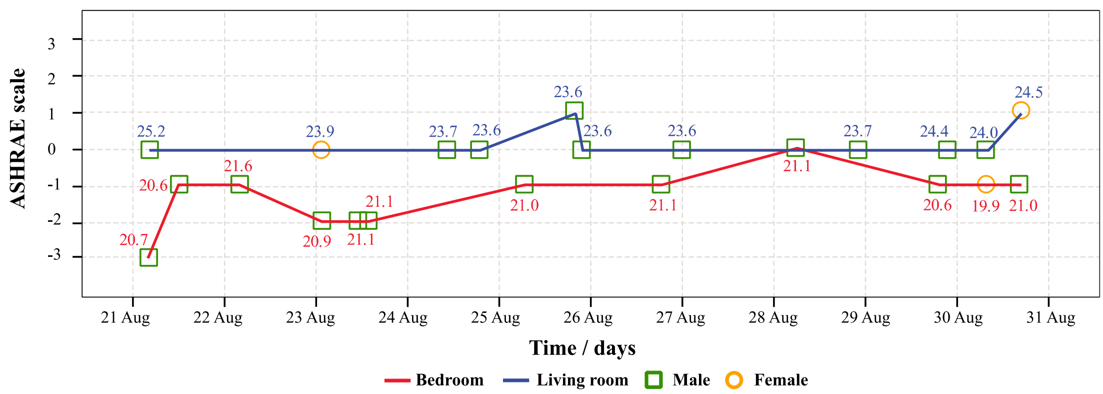


Figure 6.13 Scatter by gender and place for ASHRAE sensation votes in a multiple time-series with annotation of indoor temperature in dwelling #9 during the hot season

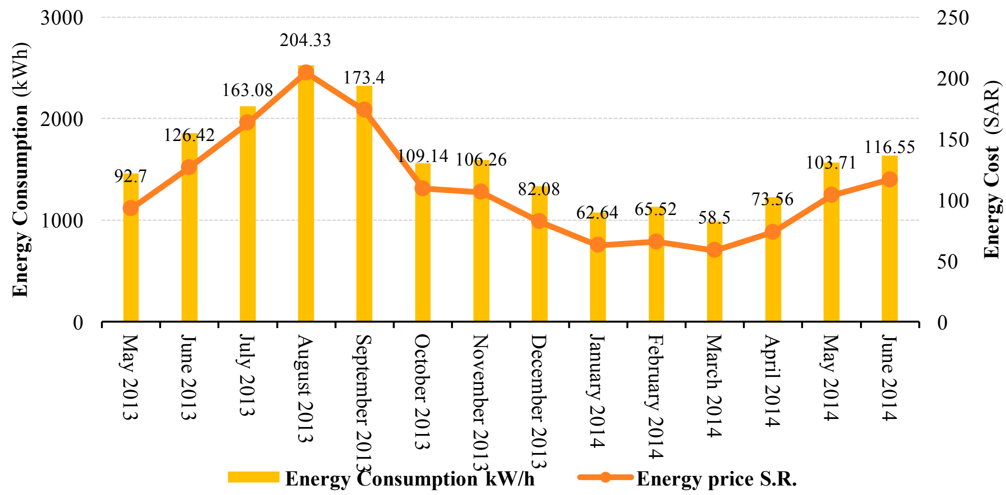


Figure 6.14 Illustration of an example of the energy consumption of dwelling #9, along with the cost of the electricity bill.

6.3.3 *Dwelling #12*

This dwelling was located in Al-Motlaq neighbourhood ~2000m away from the seashore to the east. The size of the apartment was 140m^2, with a southwest orientation and it was situated on the first floor of a three -storey apartment building constructed after 1995. Figure 6.15 shows the design layout of the dwelling, which was built of white concrete blocks and faced with a natural stone faced to the street elevations (south and west) and white plaster on the other elevations. It was constructed with a high-quality roof and external wall insulation (20cm insulated hollow bricks), with single-glazed windows and with 9.69% window to wall ratio. Alongside the use of fans in the dwelling, the type of mechanical ventilation operated is split unit AC. The split units are not maintained very often, being only cleaned once or twice a year.

The family who live in the flat consist of two adults and three children. This family is classified within the mid-income household group in this study with annual income is between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were the house renter and his wife. The husband was in his thirties and overweight, and the wife was in her twenties and also slightly overweight. As the husband worked in the education sector as a teacher, he spent most of his day at work, while his wife was in the home. They both preferred to spend most of their time in the bedroom, away from the noise of their children. They were also dissatisfied with the dwelling's design as it was not big enough for them and intended to move to another dwelling in the near future.

The indoor physical measurements were collected from the living room in the middle of the flat and the bedroom (east, south, west), with windows in the east and south wall. It is evident from Figure 6.16 that the mean thermal performance in the flat was controlled fairly well by the mechanical system in the living room but with a slight fluctuation in the bedroom after noon. Figure 6.17 shows in detail how the indoor environment of the apartment behaved in relation to the outside conditions. The bedroom appears to be 5K colder than the living room. It is also clear that the bedroom temperature has been significantly affected by the outdoor conditions. This outcome might be related to the location of the bedroom, with a large solar radiation ingress during the day from the east, south and west sides. However, it evident that the living room benefits from the buffering of the bedrooms, leaving the mean temperature continually stable at around 25°C. The humidity in the bedroom fluctuated between 55% and 75% relative humidity, while in the lounge relative humidity was less than 65%.

The higher humidity readings in the bedroom may also have resulted from its location within the flat, close to the bathroom and the kitchen.

Regarding the ASHRAE sensation scale, the householder's responses fluctuated and were irregular, as shown in Figure 6.19 and Figure 6.20. It is obvious that dwellers were not able to cope well with the internal conditions, due to the fluctuation of the indoor temperature. In addition to that, it is possible that the users felt the outgoing thermal radiation from the outer walls, as the apartment is oriented south and exposed to the sun all through the day. However, the male seemed to be feeling warmer than the female, with an outlier of feeling cold in morning of the 25th of August, with 22ºC. On the other hand, in the cool season, the occupants felt cool and slightly cool in the early morning and at midnight in the bedroom, whereas the sensation reported in the living room was quite different. This could be related to the living room having no ventilation access except the mechanical one, which reduced the air flow that affected the sensation votes.

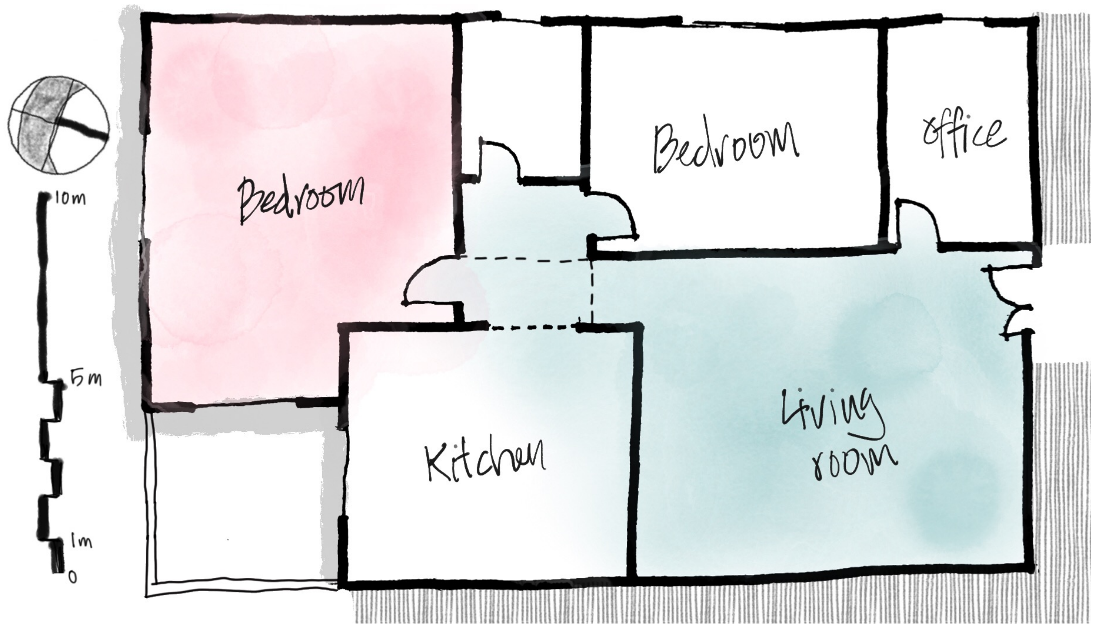


Figure 6.15 The design layout of dwelling #12

In terms of temperature preferences, the occupants generally preferred to have more cooling in both rooms. This preference could be related to the infrequent operation of fans in the bedroom (3% of the responses) and around 50% of their total responses refer to the opening of the internal door, that distributes the cooling into the other spaces in the flat. The adaptation behaviour in the cool season, however was different, as more than 50% of their responses included the operation of windows and 30% of doors. This behaviour might be due to the satisfactory outdoor conditions, that make the opening of internal doors and windows comfortable for air flow circulation.

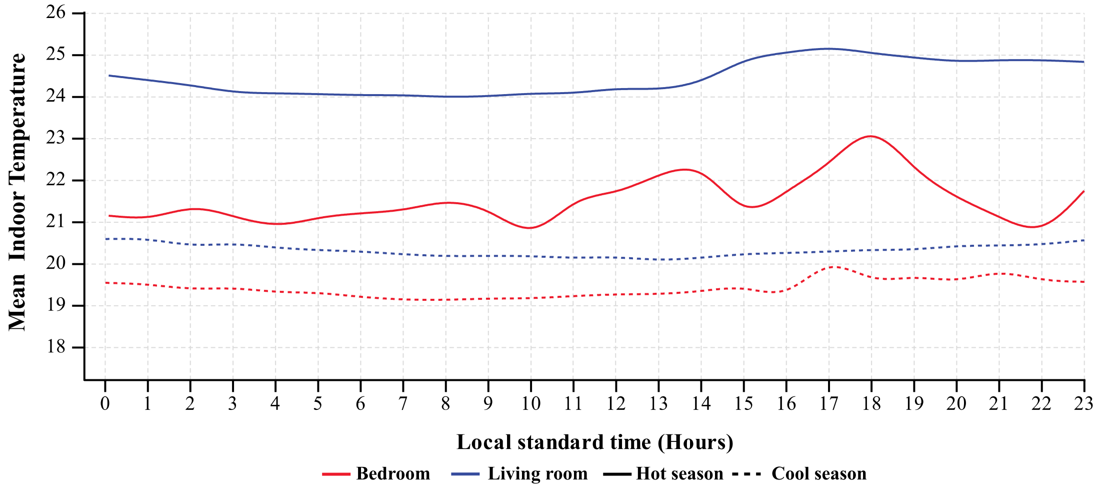


Figure 6.16 The performance of the average indoor temperature of the bedroom and living room of dwelling #12 in both season within a 24-hour time series.

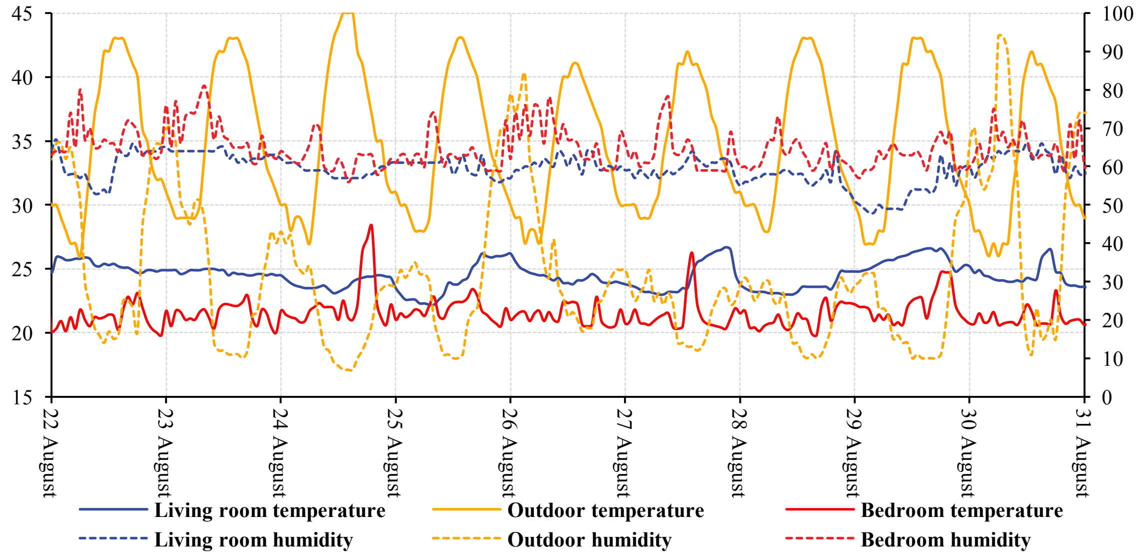


Figure 6.17 Plot of physical measurements of bedroom and living room of dwelling #12, along with outdoor conditions during the study period in the hot season.

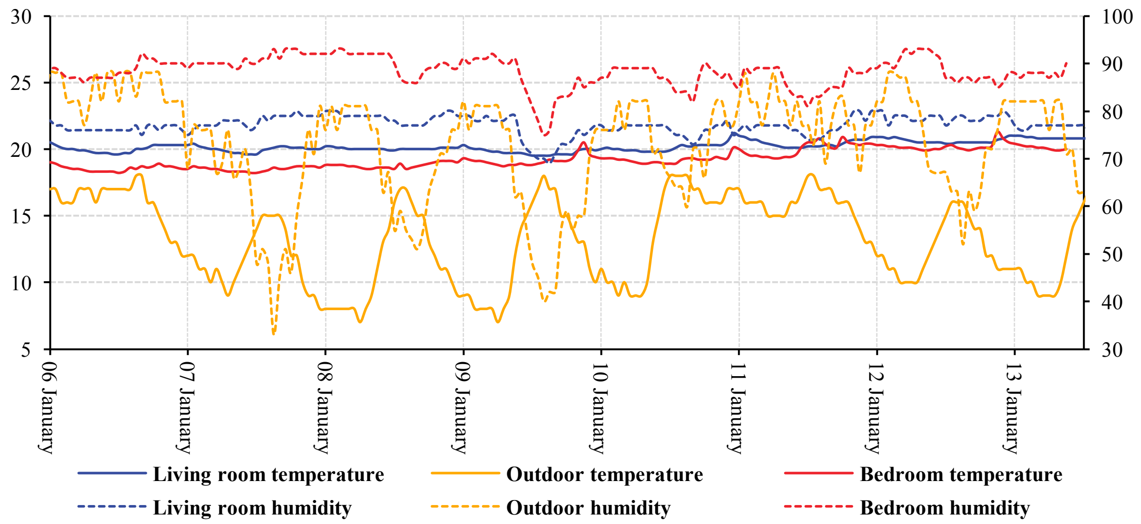


Figure 6.18 Plot of physical measurements of bedroom and living room of dwelling #12, along with outdoor conditions during the study period in the cool season.

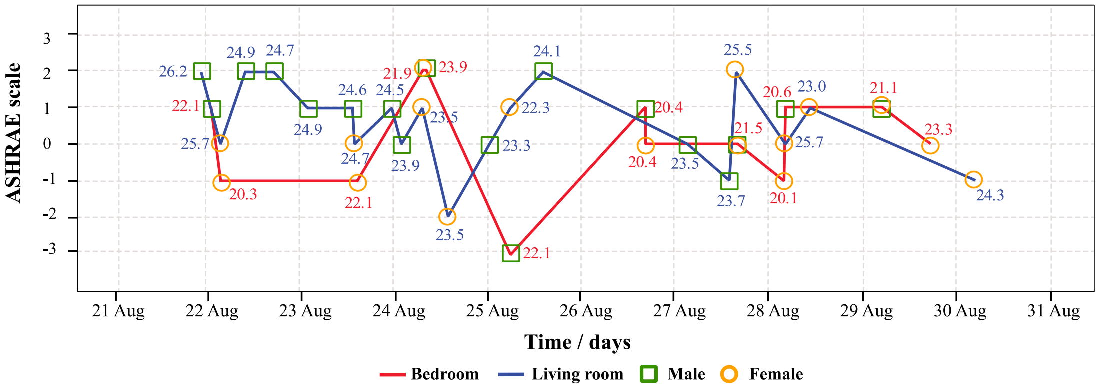


Figure 6.19 Scatter by gender and place of ASHRAE sensation votes in a multiple time series, with annotation of indoor temperature in dwelling #12 during the hot season

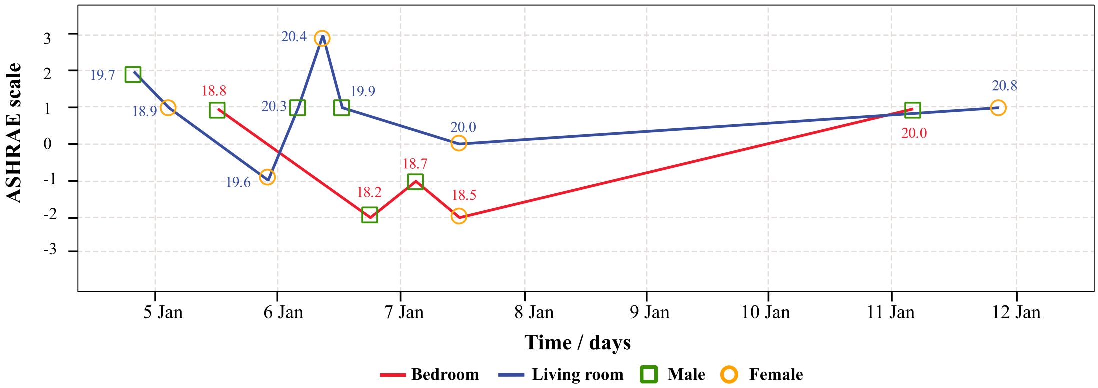


Figure 6.20 Scatter by gender and place of ASHRAE sensation votes in a multiple time series, with annotation of indoor temperature in dwelling #12 during the cool season

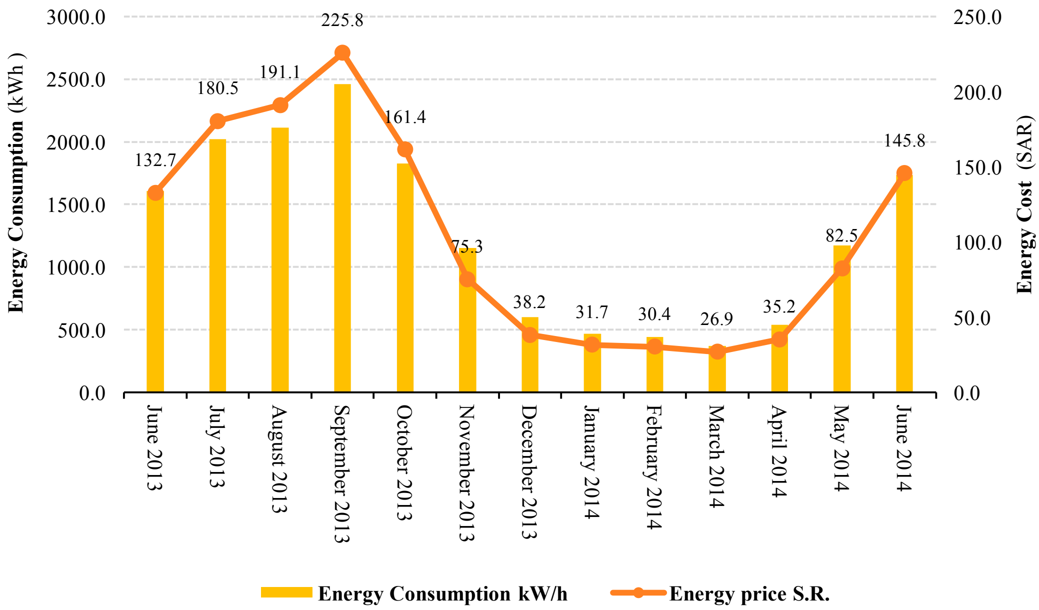


Figure 6.21 Illustration of an example of the energy consumption of dwelling #12 along with the cost of the electricity bill

Regarding electricity consumption, the householder stated that they operate the AC from March and do so until November, over daytime, and from March to October during the night. During August 2013, the energy bill was 191 SAR (£32) with a total of 2,112 kW/h electricity consumption, as shown in

Figure 6.21. This amount of money is very high compared to the other dwellings of the same size. The bill was greater in the following month, with a total of 2,460 kWh. The total cost of the energy bill in 2013 was 1,197 SAR (£218) with 14,622 kWh electricity consumption, and due to the low monthly consumption there will be no change to the cost under the new electricity tariff. Thus, the amount of energy used in this dwelling is about 104.4 kWh/m^2 per annum, and the share per person is ~2,924.4kWh per capita per annum.

Furthermore, as 70% of the cost of the electricity bill is subject to the cooling demand, the operational cost of the cooling system for this flat included the cost of electricity bill and the cost of the AC system maintenance, which was around 900 SAR (£163.65) for a single maintenance visit, was 2,574.94 SAR (£168.17) per annum.

6.3.4 *Cluster A: conclusions*

As these three dwellings all have insulation, are of a similar age and behave fairly similarly, a brief comparison should highlight the hidden factors between them that may affect performance. It is clear that the orientation of the dwelling is chiefly affecting the thermal behaviour of the building and, consequently, their energy consumption. In apartment number twelve, for example, a comparatively large amount of electricity consumption of 104.4 kWh/m^2 was expended to achieve a reasonable indoor temperature; however, the users were still not satisfied with the indoor conditions. In house number five, moreover, the electricity consumption per square metre of 109 kWh was also high, when compared to flat number nine, where a constant temperature was produced by the HVAC system throughout the day for lower electricity consumption of only 90.9 kWh/m^2 per annum. On the other hand, while the operational cost of the cooling system for dwellings 9 and 12 would not change, the future cost for dwelling #5 would increase by 14%, due to the high energy consumption.

Another notable factor regarding flat nine was the quality of the mechanical ventilation in the dwelling and its maintenance. As the AC system had a regular maintenance and was checked every couple of months, the electricity consumption was significantly lower afterwards and the production of the cooling better.

6.4 Cluster B

6.4.1 *Dwelling #1*

This dwelling was located in the South of Rakah neighbourhood ~3000m away from the seashore to the east side. The size of the apartment was 160m^2, southwest oriented and situated on the top floor of a three -storey apartment building. The building was constructed after 2005, of 20cm hollow concrete blocks with cement and light brown coloured plaster on all elevations. The layout of the apartment is shown in Figure 6.22. The occupant renting the flat had no idea if the building had any insulation, but it did have double glazed windows, with 10.8% window to wall ratio. The type of the mechanical ventilation operated in the flat was split unit AC with window AC unit systems in some of the rooms. The AC units were not maintained very often and were cleaned only once or twice a year.

The family who live in the apartments consist of a couple only, classified within the mid-income household group in this study, with annual income between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were the apartment renter and his wife. The husband was in his thirties and heavily overweight and his wife was in her twenties and slightly overweight. As the husband worked at the municipality and his wife at a school, they spent less than ten hours a day in the flat, so they left in the morning and came home at 3pm. They both preferred to spend most of their time in the living room watching the TV. The occupants were very satisfied with the design of the flat as well as with its thermal environment.

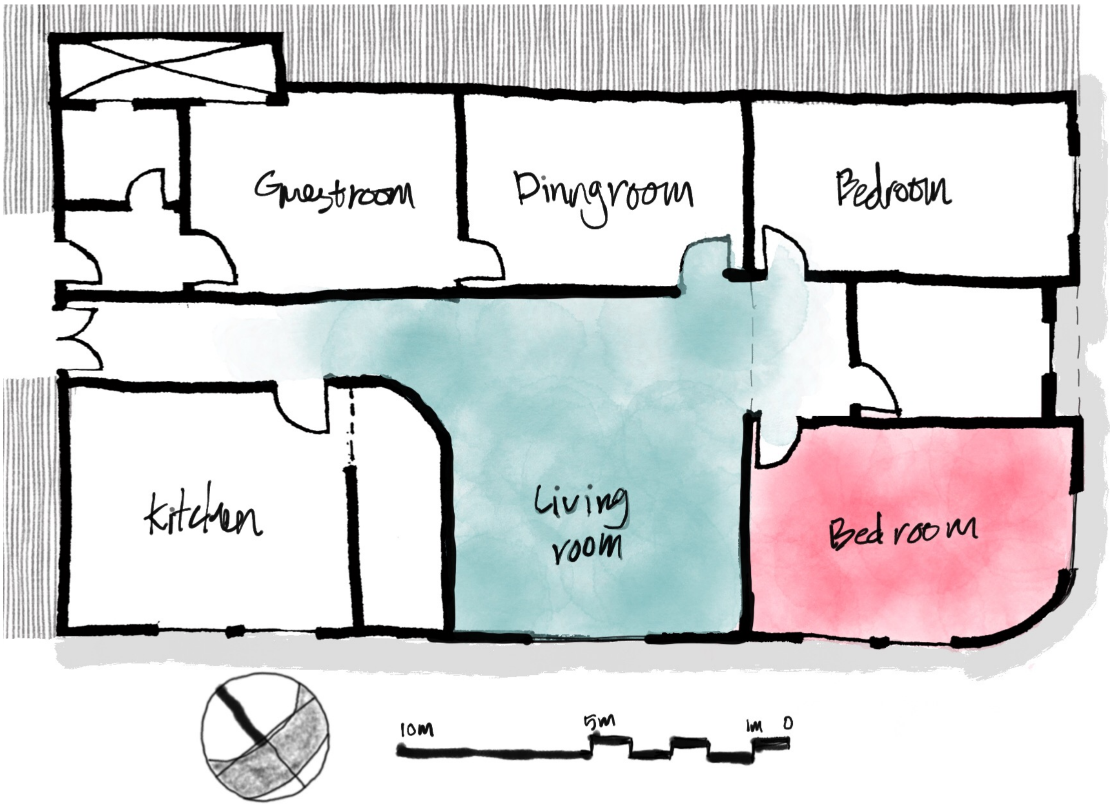


Figure 6.22 The design layout of dwelling #1

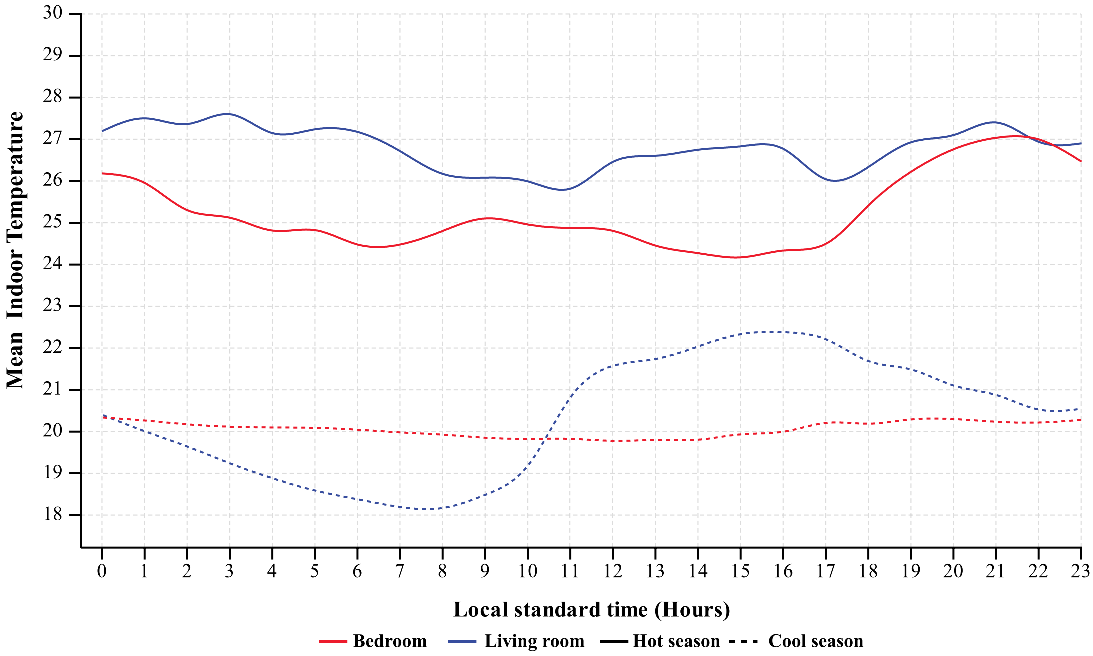


Figure 6.23 The performance of the average indoor temperature of the bedroom and living room of dwelling #1 in both seasons within a 24-hour time series

The indoor physical measurements were collected from the living room (southwest) and the bedroom (southeast and southwest). Figure 6.23 shows that the indoor temperature varied irregularly in both rooms in the hot season. Figure 6.24 shows in detail how the indoor conditions responded to the outside condition in summer. However, Figure 6.23

shows a clear evidence of the impact of the afternoon solar radiation to the living room in the cool season. Moreover Figure 6.25 clearly illustrates that strong association with ambient conditions. Although it is hard to tell the history of this property, it is obvious that it was built without insulation. It is also obvious that both rooms performed similarly in the first five days. As the outside temperature fell, room temperature started to increase once the direct west sun radiation hit the west wall. The temperature then gradually fell until it settled in the morning at about 25ºC. However, the temperature in the lounge was much higher than in the bedroom after the 25th of August, when the occupants travelled for the weekend. After that period, the lounge temperature did not settle back down to its previous condition. In fact, it even recorded higher temperatures than the outside temperature of 31ºC on more than four occasions. Furthermore, the location of the flat, on the top floor and perhaps without roof insulation, might play a fundamental part in the indoor thermal conditions experienced. The control of humidity in the living room was better than in the bedroom, where the humidity in the living room fluctuated within the range of 30% to 60% relative humidity, while in the bedroom it was normally above 60% relative humidity, which was related to the occupants' activities.

Figure 6.26 shows that on the ASHRAE sensation scale, the dwellers responded almost on the cool side of the sensation scale in the first week, whereas after the weekend period, when the house was unoccupied, the thermal performance changed to be feeling warmer in the living room and cooler in the bedroom, the thermal sensation altered erratically. Moreover, the occupants felt neutral or on the cool scale sixteen times, with temperatures between 25ºC and 32.7ºC, with an outlier of feeling cold at 27.5ºC just before the midday on the 28th of August. Conversely, the dwellers had noticed the heat of the solar radiation in the living room four times before midnight and voted warm and slightly warm along with temperature over 28.9ºC, demonstrating a clear adaptation to higher temperatures within the flat.

In terms of temperature preferences, most of the preferences votes did not relate clearly to the indoor temperatures recorded. However, the occupants voted to prefer to be cooler in the living room more than in the bedroom. This preference might relate to the location of the living room in the middle of the apartment, as well as its orientation facing southwest. The location of the living room in an area opening to all other spaces encouraged more activities and movement, as well as a great amount of energy to get to the cooling level desired. Interestingly, around 26% of the total responses included the opening of the internal door into other indoor space, which might be due to the preconception of the outdoor condition that makes the opening of internal doors a more effective choice.

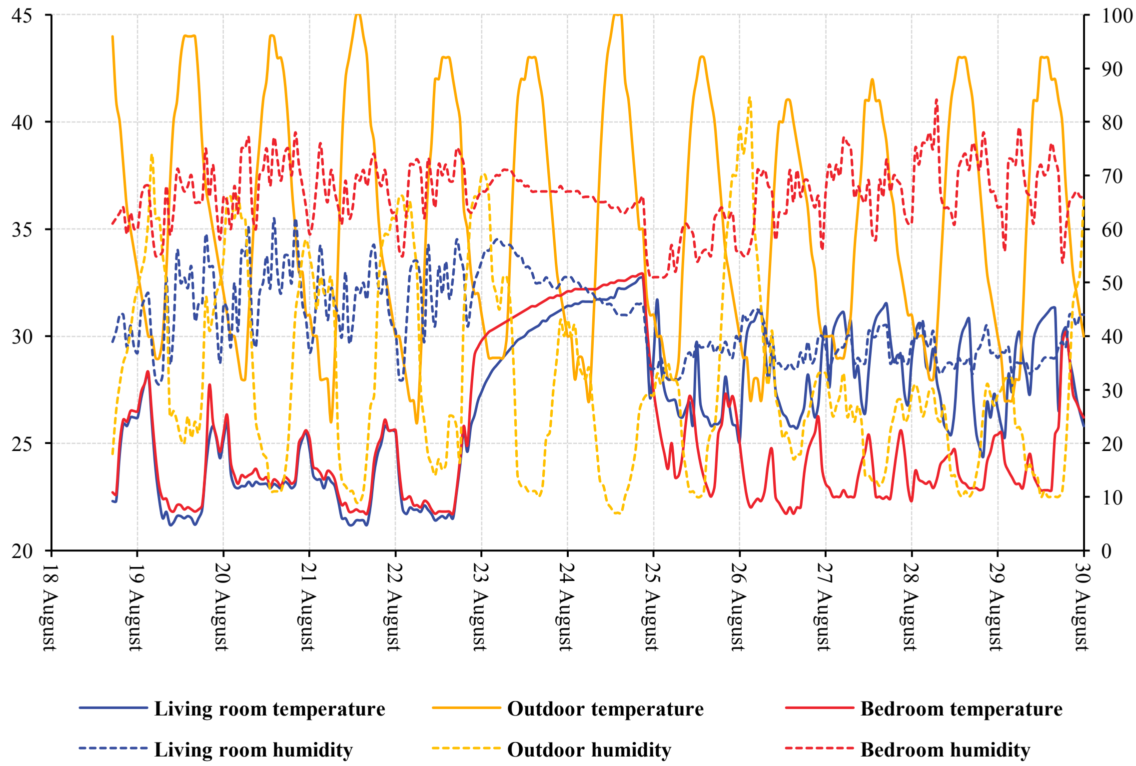


Figure 6.24 Plot of physical measurements of bedroom and living room of dwelling #1 along with outdoor conditions during the study period in the hot season

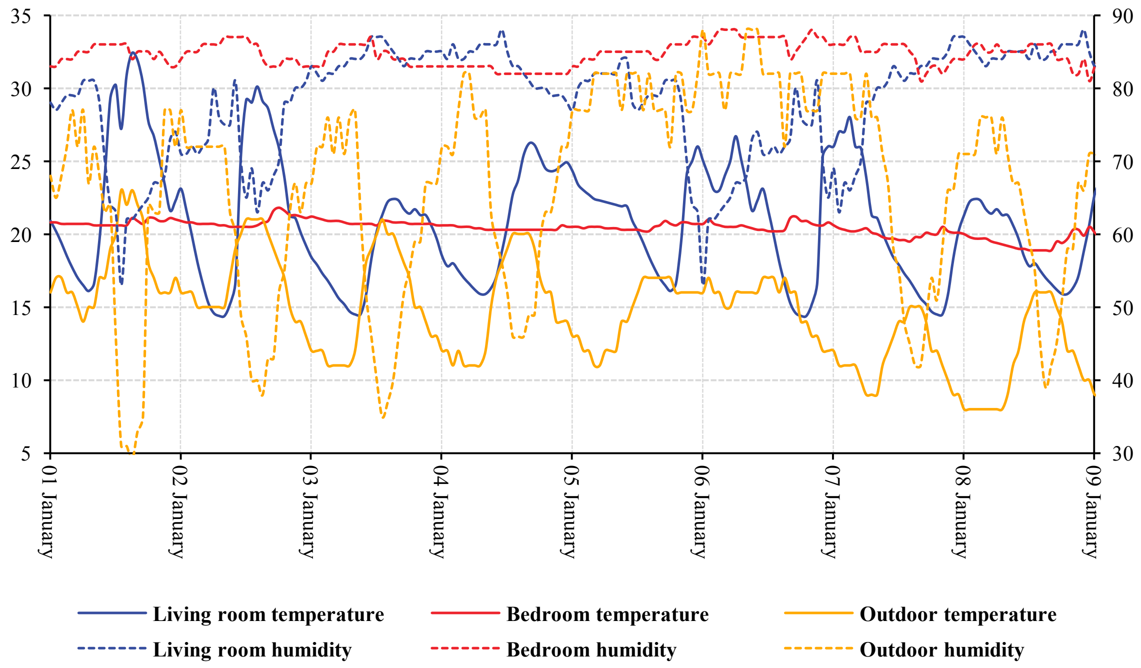


Figure 6.25 Plot of physical measurements of bedroom and living room of dwelling #1 along with outdoor conditions during the study period in the cool season

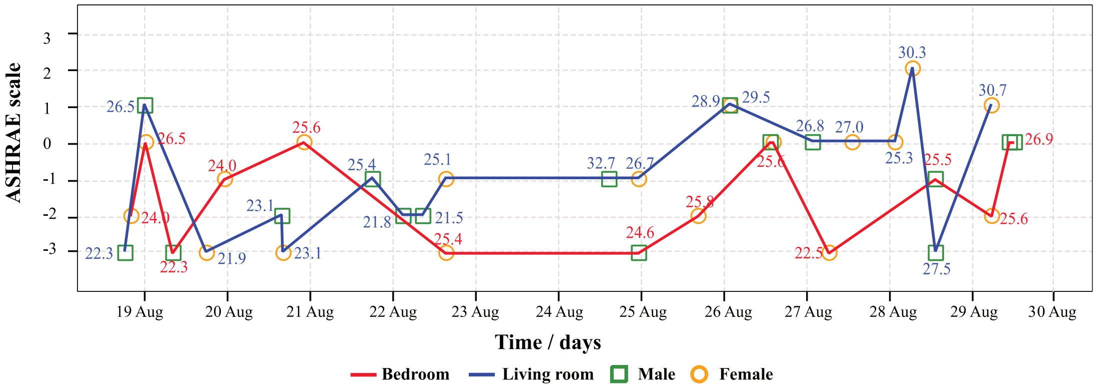


Figure 6.26 Scatter by gender and place of ASHRAE sensation votes in a multiple time-series with annotation of indoor temperature in dwelling #1 during the hot season

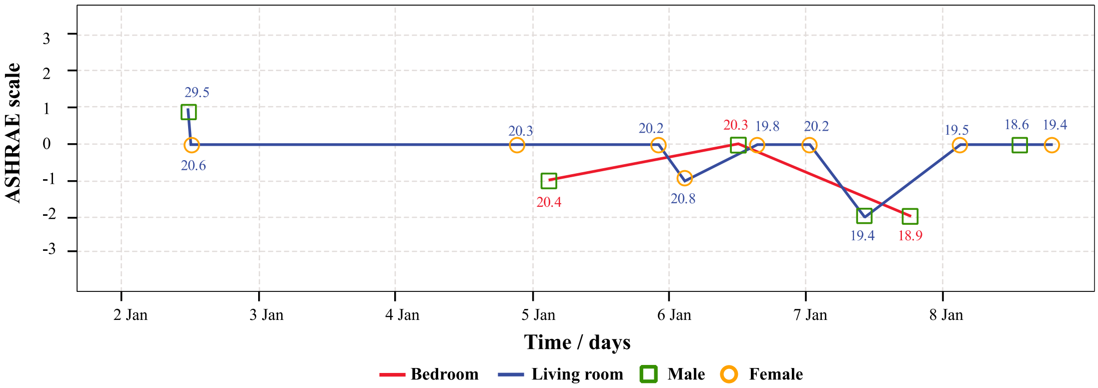


Figure 6.27 Scatter by gender and place of ASHRAE sensation votes in a multiple time-series, with annotation of indoor temperature in dwelling #1 during the cool season

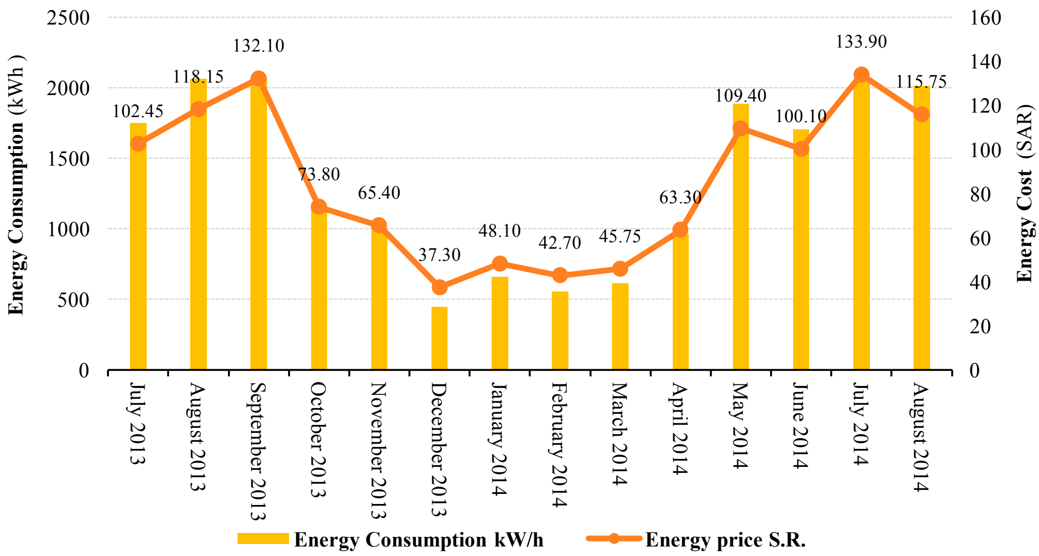


Figure 6.28 Illustration of an example of the energy consumption of dwelling #1 along with the price of the electricity bill

Regarding the electricity consumption, the householder stated that they operated the AC from March and until November every year. During August 2013, as shown in Figure 6.28, the energy bill was 118 SAR (£.5) paid for a total of 2060 kW/h of electricity consumption. The annual energy bill in 2013 was 970 SAR (£176.3) for

15200 kWh electricity consumption, and due to the low monthly consumption, there will be no change to the cost under the new electricity tariff. The amount of energy in this dwelling is about 95 kWh/m^2 per annum and the share per person is ~7,600 kWh per capita per annum.

As 70% of the cost of the electricity bill is subjected to the cooling demand, the operational cost of the cooling system for the four cooled rooms in this dwelling included the cost of electricity bill and the cost of the AC system maintenance, which is 1,200 SAR (£218.2) for a single maintenance visit, is around 2768.15 SAR (£503.3) per annum.

6.4.2 *Dwelling #3*

This dwelling was located in Al-Safa neighbourhood ~2600m away from the seashore to the east. The size of the house was $450m^2$, northeast oriented and located centrally within the street. This single-storey house was constructed in the eighties with a single course of 20cm hollow concrete blocks and coated with cement and white plaster. Figure 6.29 shows the design layout of the dwelling, which was constructed without any insulation and has single glazed windows with 31.25% window to wall ratio. The type of mechanical ventilation operated in the house is split unit AC with window AC units in some of the rooms. The AC units are not maintained very often, being cleaned only when needed.

The family who rented this house consisted of three adults, two teenagers, a housekeeper, and a driver. This family was classified within the mid-income household group in this study, with annual income between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were two females, a single mother and her adult daughter. The mother was at a healthy weight, in her sixties, while her daughter was overweight in her twenties. The mother worked in the education sector, so she spent around half of the day outside the house, while the daughter was in college. They were both dissatisfied with the design and the thermal condition of the house.

The indoor physical measurements were collected from the living room (northeast) and the bedroom, as they both occupy this room (northeast and northwest) as shown in Figure 6.29. It is clear from Figure 6.30 that the bedroom temperature increases dramatically after midday, while the living room is fairly stable during the hot season and temperatures in both rooms are stable in the cool season. Figure 6.31 shows in detail the indoor conditions, with the rather difficult to explain irregularity of the thermal performance. It is apparent that the amount of heat lost and gained through the external walls was very high. The AC split unit in the bedroom, for example, was only operated when the room was occupied normally from midnight until midday. It can be seen that when the AC was switched on, the temperature slowly decreased, within a range of five degrees. However, once the sun rose at 6 am in the morning and the radiation began to hit the external wall, the temperature immediately rose and fluctuated for a couple of hours until the sun moved so that no heat was directed onto the east wall. Moreover, the temperature in the lounge was constantly unsettled and never moved below 25ºC and always appeared to be warmer than the bedroom. This is obviously because the living room was fairly huge and opened onto other parts of the house, so the efficiency of one AC split unit could not provide the enormous amount of cooling needed in such a huge area. However, the occupants felt neutral or slightly cool in the living room. Moreover, the humidity in the living room was constantly changing under the influence of the indoor activities, ranging between 45% and 80% relative humidity, while the humidity in the bedroom ranged between 40% and 70% RH.

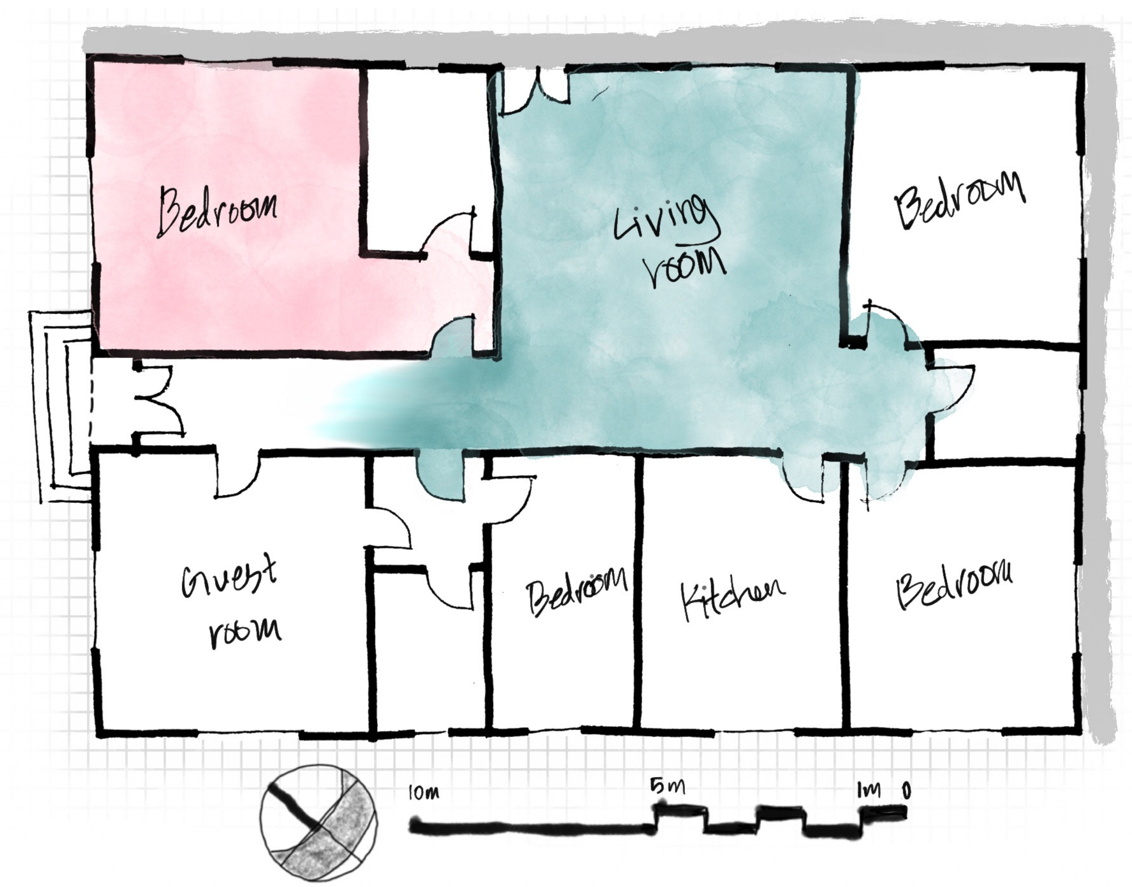


Figure 6.29 The design layout of dwelling #3

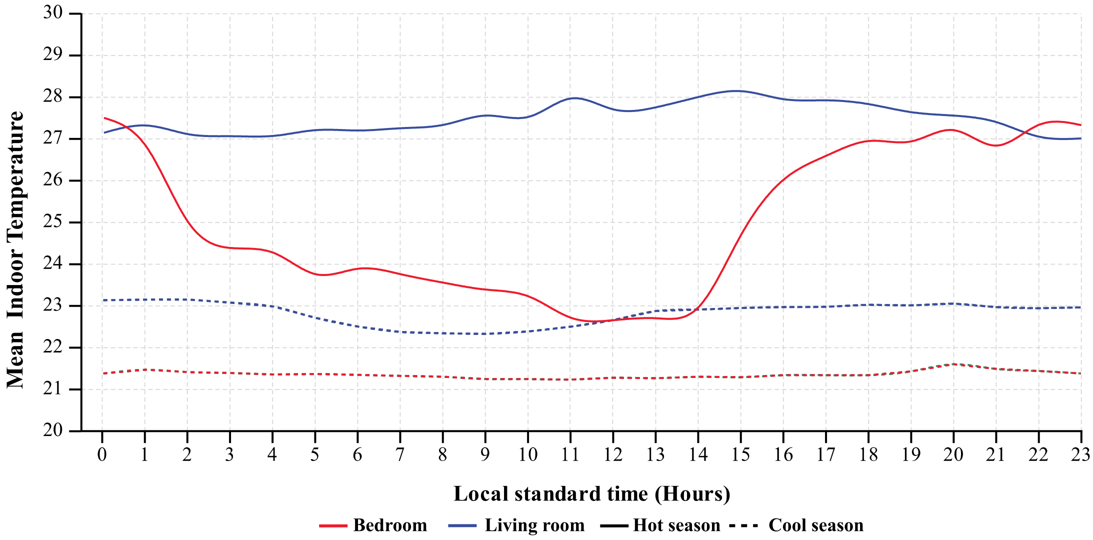


Figure 6.30 The performance of the average indoor temperature of the bedroom and living room of dwelling #3 in both seasons within a 24-hour time series.

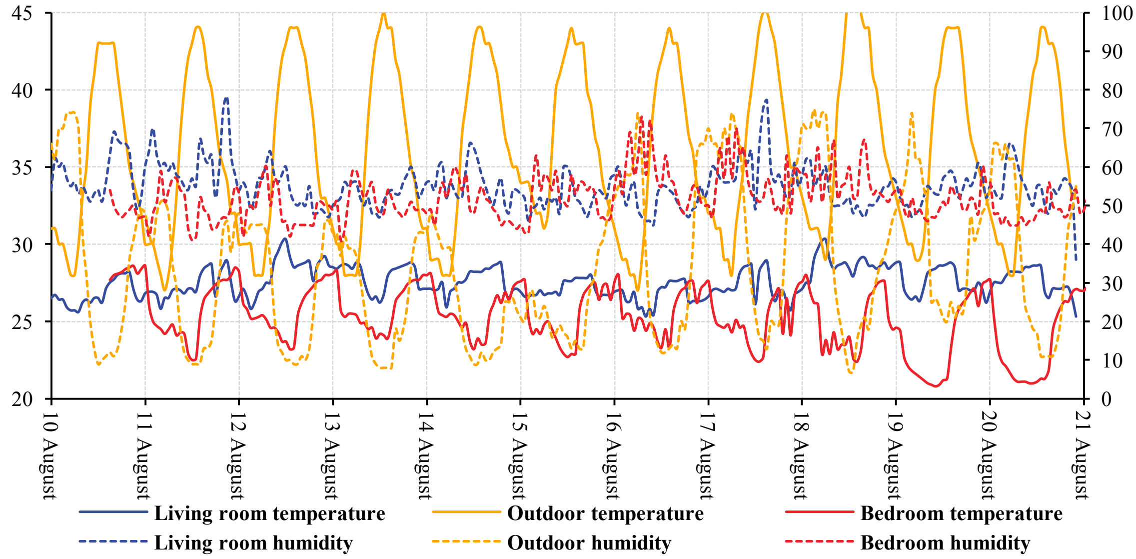


Figure 6.31 Plot of physical measurements of bedroom and living room of dwelling #3 along with outdoor conditions during the study period in the hot season.

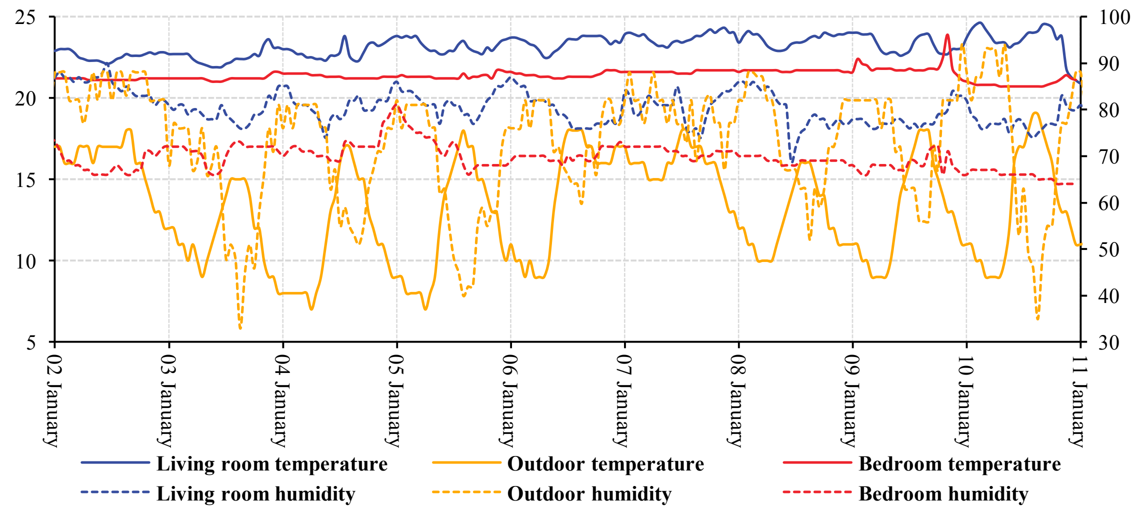


Figure 6.32 Plot of physical measurements of bedroom and living room of dwelling #3 along with outdoor conditions during the study period in the cool season.

For the ASHRAE sensation scale, the householder's responses were neutral and slightly cool. Figure 6.33 and Figure 6.34 shows the dwellers' thermal perception of the indoor temperature in both seasons. In the bedroom, the occupants seemed to be feeling cool as they never voted neutral or over in the hot season, even with temperature slightly over 27ºC. Those reported choices may be related to the fact that they filled in the survey after being in the lounge, with its warm conditions, and before sleeping at night, so the AC was switched on, and the room had cooled already. However, what is interesting is that the state of the bedroom may allow to free-float from early afternoon until midnight before using the AC, which indicates respective time lags and thermal damping comparing respective troughs and peaks between rooms. In terms of temperature preferences, the occupants always voted to prefer to be cooler in the living room. However, in the cool season, shown in Figure 6.34, the sensation votes were warm and slightly warm in the bedroom with temperatures below 21ºC. This may be related to the reduced amount of air flow in the room, or the wearing of winter clothes compounding the warm effect on the sensation vote in the cool season, as the clothing value of the occupants during the night in the cool season ranged between 0.35 to 0.62 *clo*.

Regarding electricity consumption, the householder stated that they operate the AC all the time from May and until December. During August 2013, as shown in **Figure 6.35**, they had an energy bill of 993.6 SAR (£180.7) for a total of 9508 kW/h electricity consumption. The total energy bill for 2013 was 5204 SAR (£946.2) for 56339 kWh electricity consumption. Thus, the amount of energy used in this dwelling was about 125.2 kWh/m^2 per annum and the share per person was ~8048.4 kWh per capita per annum. However, with the new electricity tariff, their annual electricity bill could reach 8,325.82 SAR (£1513.79) per annum.

The operational cost of the cooling system for the six cooled rooms in this house, including the cost of the electricity bill and the cost of the AC system maintenance, which was 1,800 SAR (£327.3) for a single maintenance visit, was around 7,903.9 SAR (£1,437.1) per annum. However, with the new electricity tariff, the annual operational cost could reach up to 11,026 SAR (£2,004.7), without factoring in the cost of replacement of any faulty parts during maintenance.

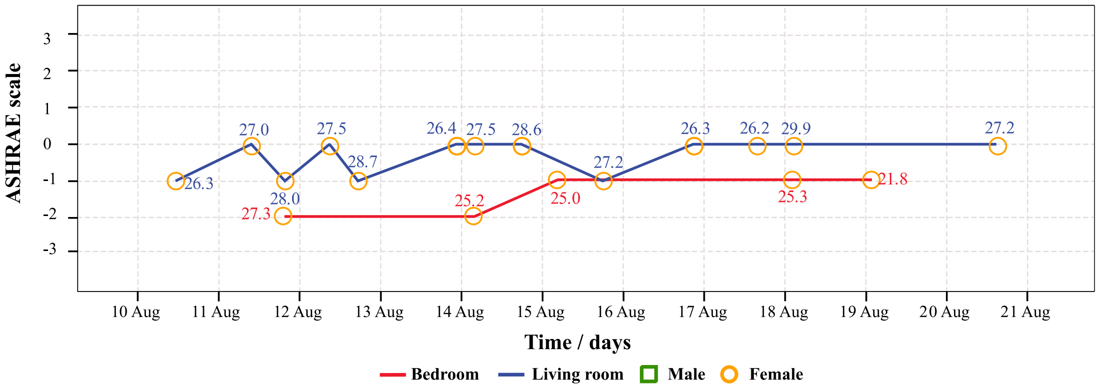


Figure 6.33 Scatter by the place of ASHRAE sensation votes in a multiple time series with annotation of indoor temperature in dwelling #3 during the hot season

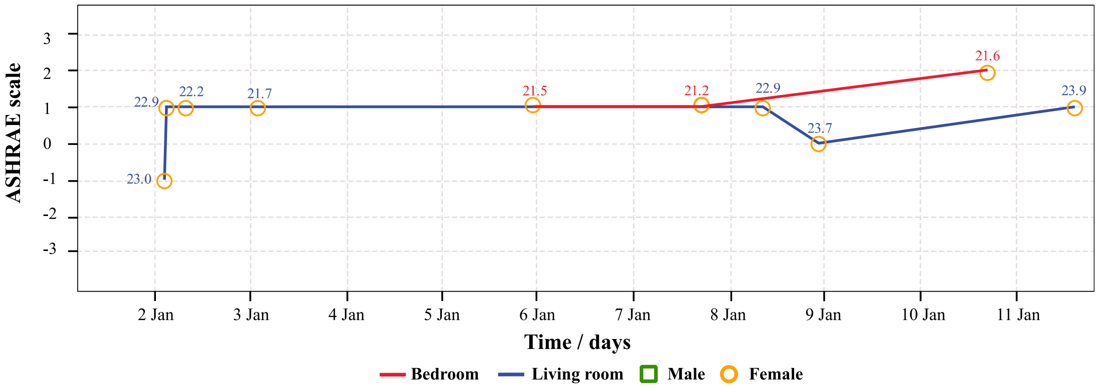


Figure 6.34 Scatter by gender and place of ASHRAE sensation votes in a multiple time series, with annotation of indoor temperature in dwelling #3 during the cool season

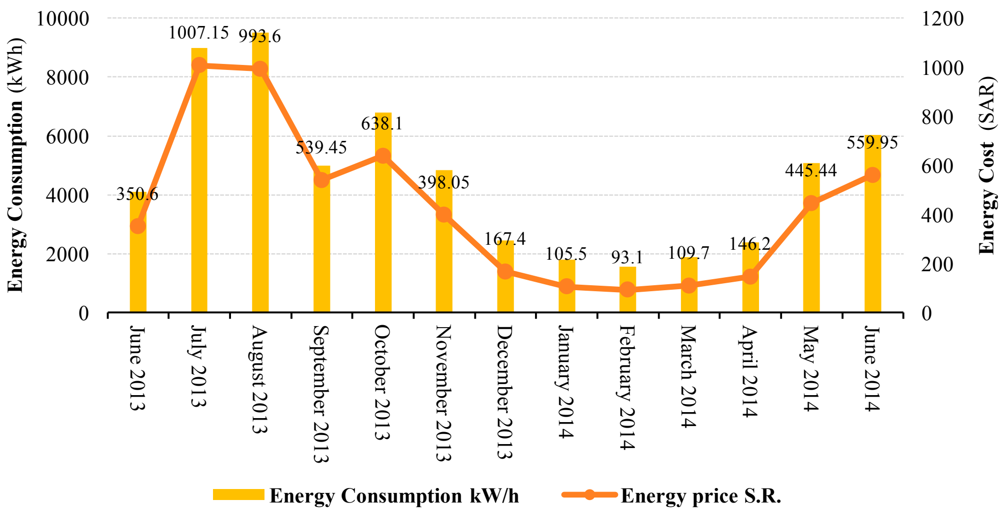


Figure 6.35 Illustration of an example of the energy consumption of dwelling #3 along with the cost of the electricity bill

6.4.3 *Dwelling #6*

This two-storey detached house was located in Al-Corniche neighbourhood ~600m away from the seashore to the east. The size of the house was about 700m^2, northeast oriented and located centrally within the street and it was constructed in or after 2005

(Figure 6.36). It was built of white lightweight concrete blocks and coated with natural stone on the main eastern façade, with light beige colour plaster on the other elevations. It was constructed with a high-quality roof and external wall insulation (25cm thickness of the blocks including the insulation inside the external walls), and double-glazed windows and with 18.65% window to wall ratio. Unlike the other cases, this dwelling has a nice plantation around the house and pergola. Furthermore, together with the use of ceiling fans in all occupied rooms, the house has mechanical ventilation in the form of a central HVAC system with several split units in some parts of the house and all rooms' ceilings are covered by a suspended ceiling concealing the ducts, piping and HVAC system. The mechanical systems are regularly maintained, around twice a year.

The family living in the house consisted of a father, mother, male teenager, three children and a housemaid. This family was classified within the high-income household group in this study, with annual income between 220 to 440 thousand SAR (£40-80 thousand). The subjects involved in the study were the house owner and his wife, who are both in their fifties and slightly overweight. As the husband worked in ARAMCO, he spent about ten hours a day in the house while his wife, an interior designer, was home-based for her work. Although they were both satisfied with the design of the house, they both preferred to spend most of their time in the bedroom section, as it was quieter than the rest of the house. In fact, the male occupant claimed that the house was too big for them, as two of his sons were studying in a different city, so they barely used the spaces.

The indoor physical measurements were collected in the east and west facing living room and the east facing bedroom, as shown in Figure 6.36. Moreover, Figure 6.37 shows that by midday the indoor temperature increases by more than three degrees in the bedroom while there are many fluctuations in the living room temperatures. Figure 6.38 shows in detail how the indoor conditions performed. It is clear that the temperature in the living room was warmer than the bedroom by an average of five degrees. The occupants stated that the AC in the house was only operated when the rooms were occupied and they switched on the AC system for around 20 to 45 minutes every two hours in the day time and operated the ceiling fan for air movement. Furthermore, the operation of the AC system in this house was limited to six months in the year.

Figure 6.36 The design layout of dwelling #6

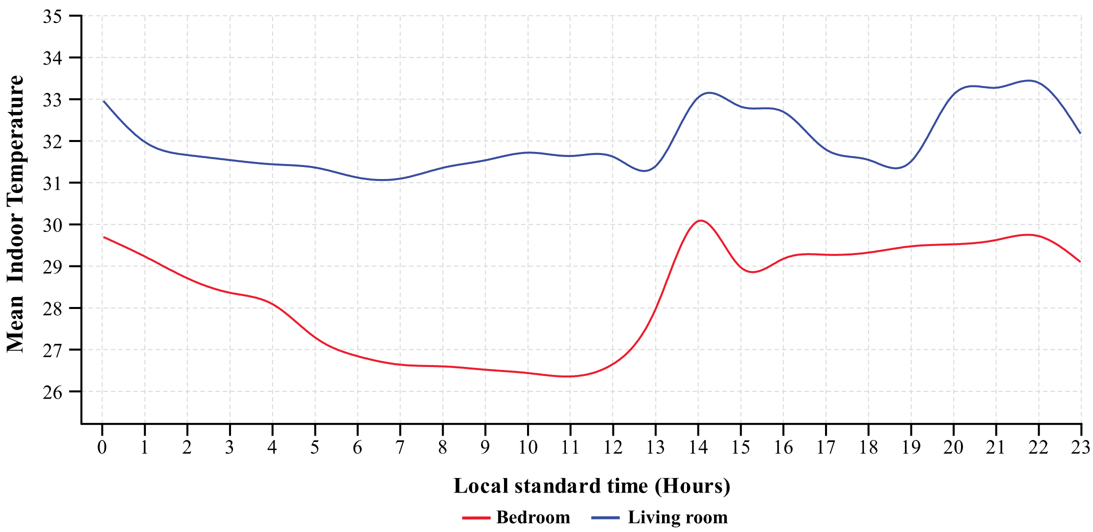


Figure 6.37 The performance of the average indoor temperature of the bedroom and the living room of dwelling #6 in the hot season within a 24-hour time series

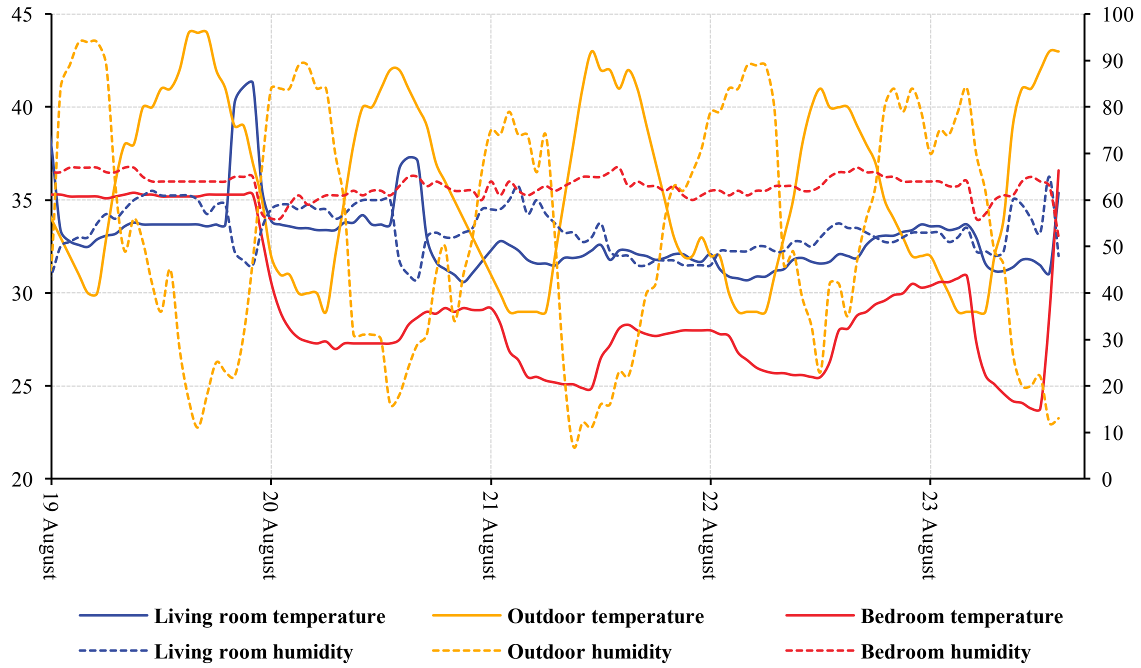


Figure 6.38 Plot of physical measurements of bedroom and living room of dwelling #6, along with outdoor conditions during the study period in the hot season

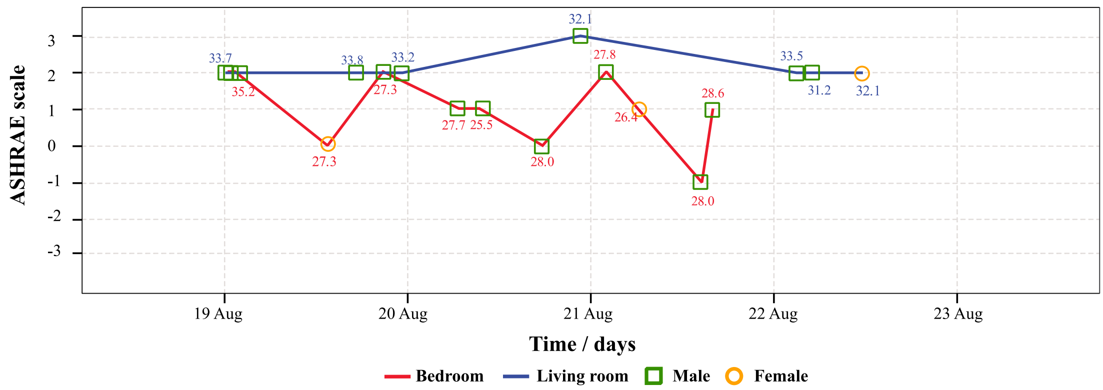


Figure 6.39 Scattering by gender and place of ASHRAE sensation votes in a multiple time series with annotation of indoor temperature in dwelling #6 during the hot season

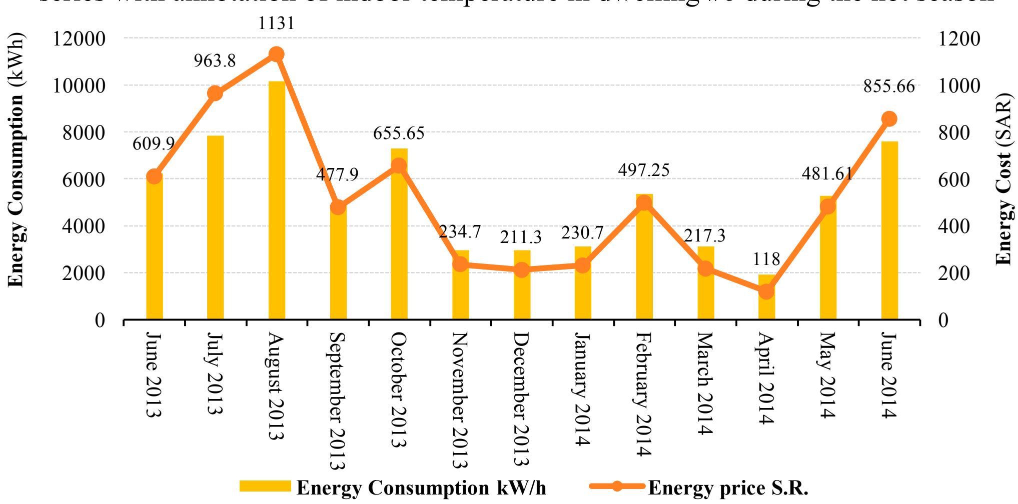


Figure 6.40 Illustration of an example of the energy consumption of dwelling #6 along with the price of the electricity bill

As the house was well insulated, there was no clear indication of a relationship between the external temperature and the internal temperature as long as the AC operated. In the bedroom, for example, when the AC was switched on, before the occupants going to bed at midnight, the temperature slowly decreased from just below 30ºC to 25ºC and remained at this temperature until midday. Conversely, the temperature in the lounge was continuously warm and never fell below 30ºC. This is obviously because the living room was east-west facing, being large and opening to almost all other parts of the house. Due to the occupants' preference to be in a warm condition, it appears that, in summer, the living room was even warmer than the outside climate overnight. However, the humidity in the lounge was lower than in the bedroom. It fluctuated in the range of 50% to 60% relative humidity, whereas, in the bedroom, humidity was always over 60% relative humidity.

Figure 6.39 shows the occupants' thermal perception towards the indoor temperature in the hot season, according to the ASHRAE sensation scale responses. It can be seen that the indoor temperature of the bedroom was unstable and changed very often causing the householders' votes to fluctuate randomly. Although the male occupant voted seven times at warm and slightly warm for temperatures between 25ºC and 35ºC, indicating he preferred to be slightly cooler, he also voted slightly cool at a temperature of 28ºC. In the living room, when temperatures rose over 31ºC the votes were always warm, apart from a single response of hot at a temperature of 32.1ºC, with a no change preference. What is surprising in this house, is that the male subject enjoyed remaining without the air conditioning and only operated the ceiling fan when he was alone. This occurred regularly, as it happened on seven occasions out of eighteen recorded responses, including two choices where he left the window open at 3pm along with an outdoor temperature over 40ºC. Moreover, one out of three responses recorded the female subject operating both the ceiling fan together with the AC. Interestingly, the proportion of time operating the AC and fan was distributed between 50% each. The subjects also used other forms of adaptation during the extreme hot season, opening the windows and doors in the proportion of 11% and 39% respectively.

Regarding the amount of the electrical consumption, the householder stated that they operate the AC from May until the end of September, over both day and night-time. During August 2013, as shown in Figure 6.40, the energy bill was 993.6 SAR (£180.6) for a total of 9508 kW/h electricity consumption. The annual energy bill in 2013 was 6,075 SAR (£1,104.5) for 62,480 kWh electricity consumption. Thus, the amount of energy in this house is around 89.3 kWh/m^2 per annum, which is around 760 Saudi Riyals (£138) per person per annum. However, with the new electricity tariff, the annual electricity bill could increase, to 9,719.8 SAR (£1,767.2) per annum.

The operational cost of the cooling system for the seven cooled rooms in this house including the cost of electricity bill and the cost of the AC system maintenance, which is around 2,100 SAR (£381.9) for a single maintenance visit, is around 9,225.13 SAR (£1,677.3) per annum. Nevertheless, with the new electricity tariff, the annual operational cost could reach up to 12,870 SAR (£2,340) without the cost of replacement of any faulty parts during maintenance.

6.4.4 *Dwelling #13*

This detached house is located in The South of Doha neighbourhood ~7000m away from the seashore to the east. The size of the house is ~350m^2, northwest oriented and located centrally within the street. This house is one storey only with a staircase for a future extension and it was constructed in the eighties. Figure 6.41 shows the design layout of the dwelling that was built of 20cm hollow concrete blocks and coated with coloured cement, without roof and wall insulation and with single glazed windows and with 31.11% window to wall ratio. The type of the mechanical ventilation operated in the house was split unit AC with some AC window systems in some parts of the house, along with a ceiling fan in the occupied rooms. The AC units were not well maintained or serviced very often, as they were only filled with Freon gas when needed; the householders stated that it was expensive to maintain the cooling system and they chose not to maintain the equipment regularly.

The family, who lived in the house consisted of two adults and six children and a housemaid. This family was classified within the mid-income household group in this study, with annual income between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were the house owner and his wife, in their forties, and both were heavily overweight. As the parents are school teachers and their children all attend schools, they spend most of the daytime outside the house. They both prefer to spend much of their time at home in the living room, as they stated ‘it is the area where the family meet’.

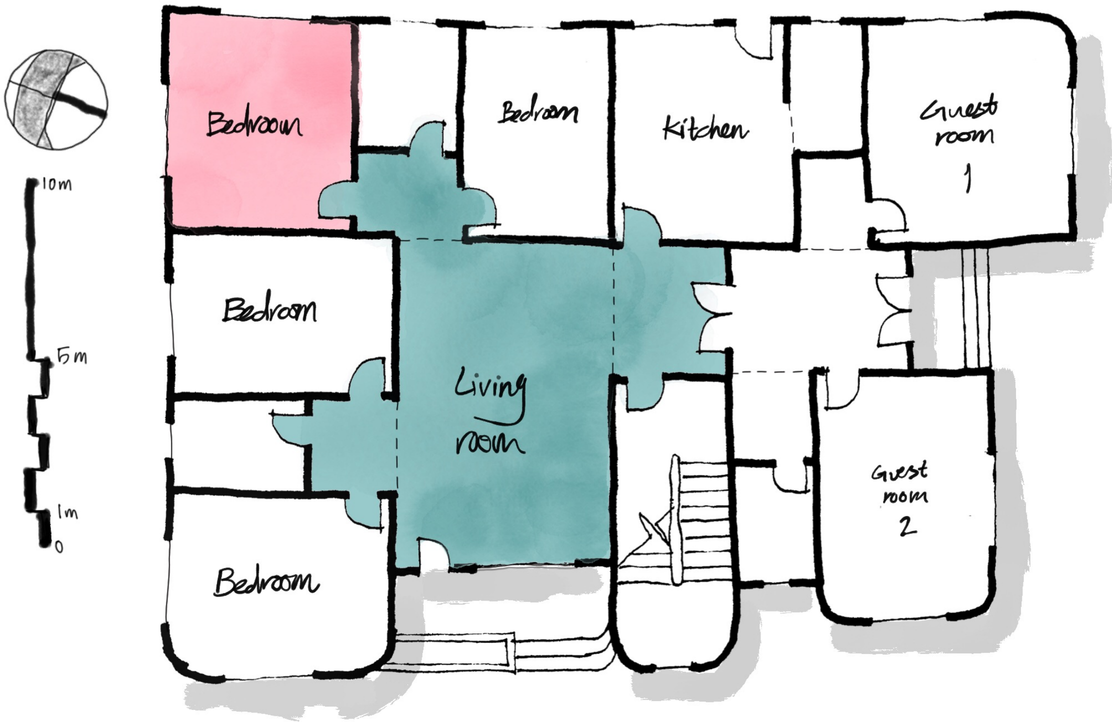


Figure 6.41 The design layout of dwelling #13

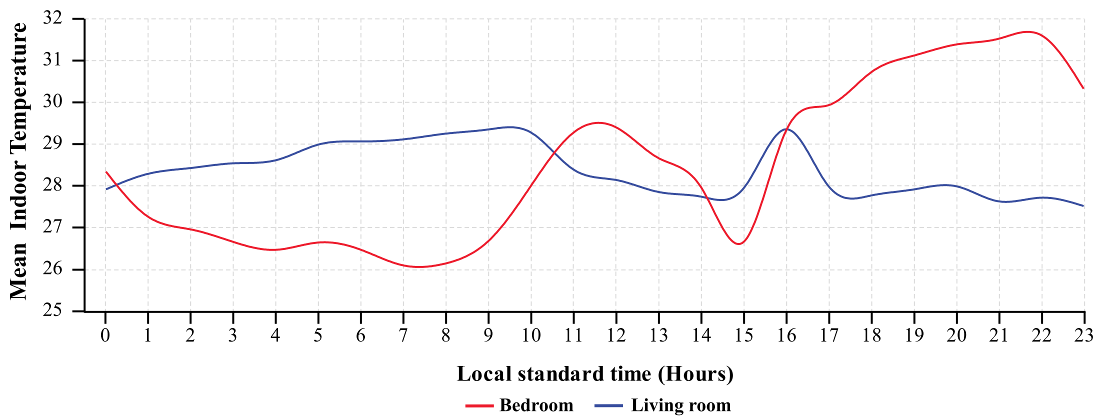


Figure 6.42 The performance of the average indoor temperature of the bedroom and the living room of dwelling #13 in the hot season within a 24-hour time series

The indoor physical measurements were collected from the east facing living room and the south and west facing bedroom, shown in Figure 6.41. Figure 6.42 shows that the thermal performance in the house fluctuated considerably around an average indoor temperature of 29ºC most of the day. Moreover, it is evident from Figure 6.43 that the occupants switch the AC on or off when they occupy or leave the rooms, and the indoor temperature differences in the bedroom are much higher than in the living room. This high temperature in the bedroom is obviously due to the west facing aspect of the bedroom, as the sun was striking the western wall by 3pm and the temperature rose gradually from ~ 26ºC to 32ºC. The living room temperatures fluctuated between 27ºC to 29ºC and were always below 30ºC, with one exceptional record of 39.3ºC reported since the readings in the house began. This exceptional outlier might be related either to the occupant leaving the door open for a long time, or the instrument having been just moved into the room, as the temperature was close to the temperature outdoors, from where it had just been moved. It is apparent that the occupied temperatures were influenced by the outdoor temperatures and rooms may allow to free-float from early afternoon until midnight. The humidity in both rooms fluctuated between 50% and 65% relative humidity.

Figure 6.44 shows the occupants' thermal perceptions towards the indoor temperature in the hot season, according to the ASHRAE sensation scale. In line with the indoor temperature of the bedroom, that was unstable and changed very often, the householder's votes fluctuated randomly. In the first four days, the votes were neutral and on the warm side of the scale associated with temperatures between 28.6ºC and 33.8ºC and the respondents desired more cooling in the bedroom. After that point, the votes changed to be always on the cool side, related to a range of temperature between 25.7ºC to 29.6ºC, and they mostly responded that they did not want to change the temperature. However, the occupants were fairly satisfied with the temperature in the living room. The responses were on the comfortable side (slightly warm, neutral, slightly cool) apart from two responses that were warm and associated with a temperature of 27.9ºC and 28.4ºC respectively. Most of these reported thermal sensations votes fell out of the adaptive limits ranges and yet were considered as ordinary liveable conditions in this house.

In terms of adaptations, the proportion of time of operating the AC was only 77% of the studied period, which might have been to reduce the electricity bill, as they claimed it was expensive. The householder also operated the fans and opened doors as a source of adaptation, in the proportion of 23% to 62% respectively, supporting the hypothesis that opening the internal doors into other indoor spaces, instead of opening windows, was preferred because of the preconception of the extreme outdoor conditions.

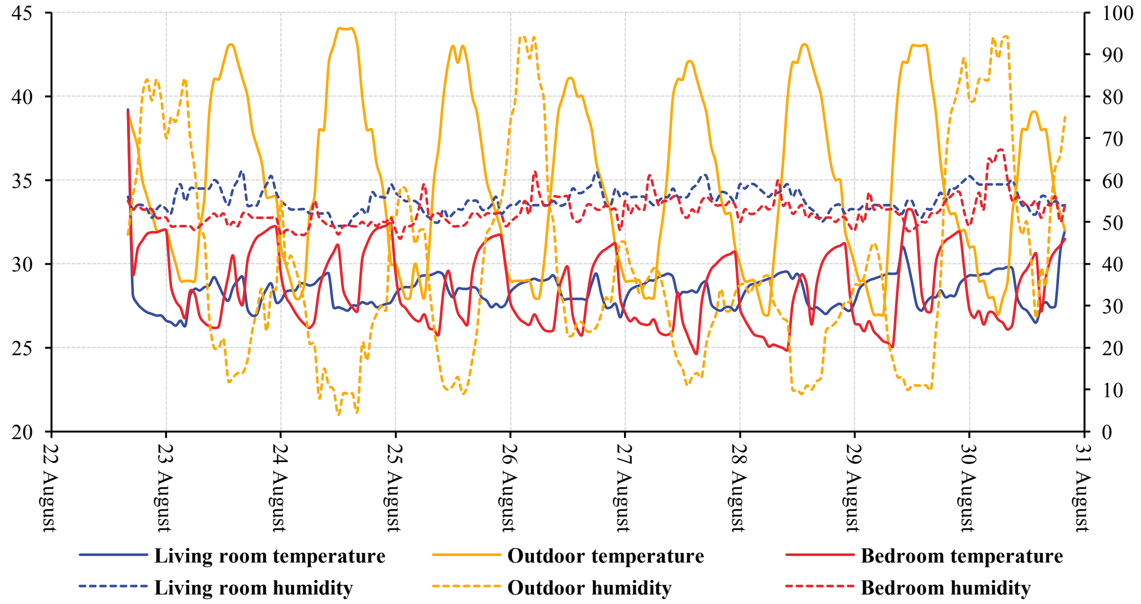


Figure 6.43 Plot of physical measurements of bedroom and living room of dwelling #13 along with outdoor conditions during the study period in the hot season

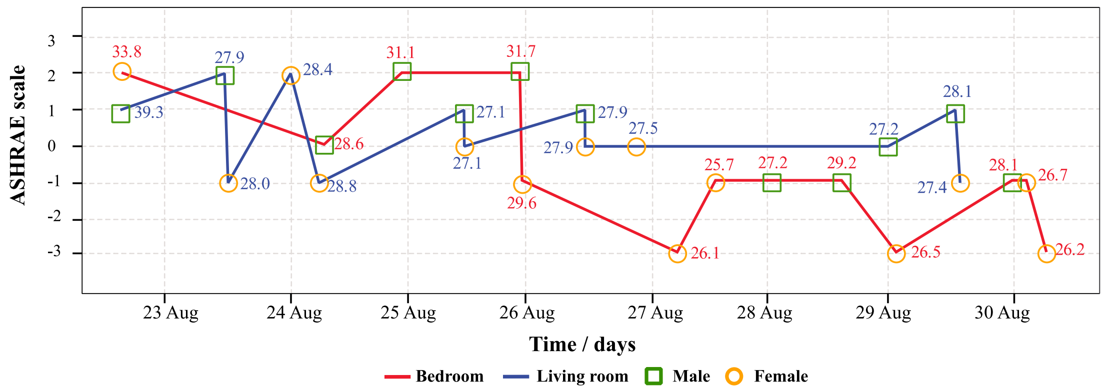


Figure 6.44 Scatter by gender and place of ASHRAE sensation votes in a multiple time series, with annotation of indoor temperature in dwelling #13 during the hot season

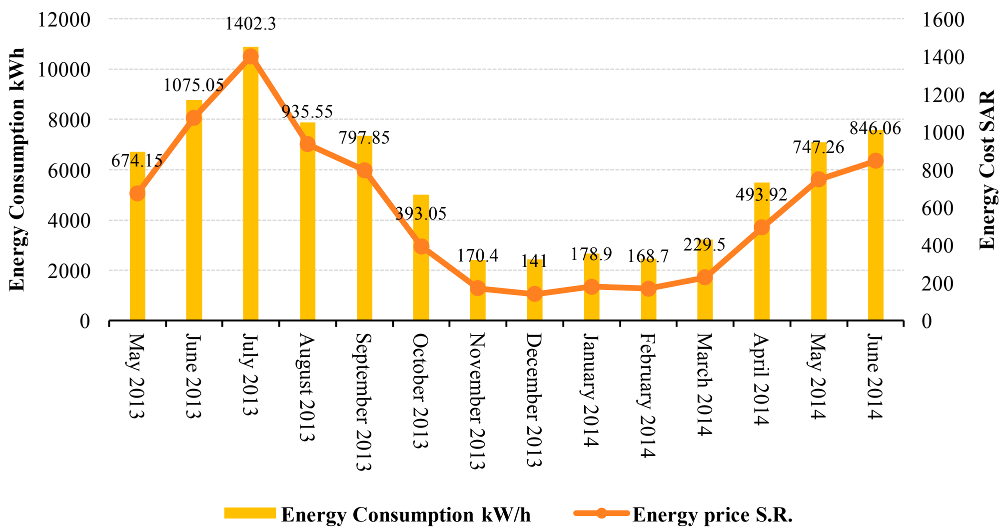


Figure 6.45 Illustration of an example of the energy consumption of dwelling #13, along with the cost of the electricity bill.

Regarding the amount of the electricity consumption, the householder stated that they operated the AC from June until the end of September over the day and night-time. During August 2013, as shown in Figure 6.45, the energy bill was 935.55 SAR (£156) for a total of 7,874 kW/h electricity consumption. This bill was somewhat less than the June and July bills of the same year, as the occupants went for a holiday at the beginning of August. The annual energy bill in 2013 was 6,733.5 SAR (£1,224) for 65,666 kWh electricity consumption. Overall, the amount of energy used in this house was around 192.4 kWh/m^2 per annum with the share per person being around 8,416.9 kWh per capita per annum. However, with the new electricity tariff, the annual electricity bill could reach 11,850.9 SAR (£2,154.7) per annum.

Given that around 70% of the cost of the electricity bill is subjected to the cooling demand, the operational cost of the cooling system for the eight cooled rooms in this house, including the cost of the electricity bill and maintenance of the AC system, which was 2,400 SAR (£436.4) for a single maintenance visit, was around 11,007 SAR (£2,001) per annum. However, with the new electricity tariff, the annual operational cost could rise by 4,500 SAR (£820) above the current price, without factoring in the cost of replacement of any faulty parts during maintenance.

6.4.5 *Cluster B: Conclusions*

Despite the fact that these four dwellings varied in terms of insulation, orientation, and size, they behaved in a reasonably similar fashion. Therefore, a brief comparison is included to highlight the hidden factors among them. Apartment #1 , for example, consumes a relatively modest 95 kWh/m^2 per annum, despite appearing to suffer from its south-westerly orientation. However, it seems that this insulated flat located on the ground floor is well-formed and placed to provide good indoor conditions that consequently produce ASHRAE sensation scale votes of neutral and slightly cool. In contrast, looking at houses numbers three and thirteen in this cluster, which were both reasonably well-oriented single storey houses of similar size and age, they consumed the most energy among the cluster. An enormous amount of electricity (192.4 kWh/m^2 in house #13 and 125.2 kWh/m^2 per annum in house #3) was consumed to achieve apparently acceptable temperatures. This higher level of energy consumption could be related to the fact that these houses were not insulated, and the number and size of windows may be excessive with more than 31% window to wall ratio.

Although house #6 was the largest in size among those four dwellings, the energy consumption per square metre was the lowest, at of 89.3kWh/m^2 per annum. This may be have been influenced by the good orientation of the house to the northeast, and the type and state of maintenance of the air-conditioning systems used, both central HVAC system and split unit AC. Moreover, a critical factor in this house was the insulation, as it was fully insulated and coated with natural stone, providing another layer of insulation. Although, in fact the ASHRAE scale mean is on the warm side, this may be explained by the occupant's attitude and daily lifestyle, which made a huge difference in comparison with the studied dwellings in this study.

6.5 Cluster C

6.5.1 *Dwelling #8*

This dwelling was located in the North of Rakah neighbourhood, ~2000m away from the seashore to the east. The size of this flat was 140m^2, and it was oriented to the southwest and situated on the top floor of a three storey apartment building constructed after 2005. Figure 6.46 shows the design layout of the dwelling, which was built with 20cm hollow concrete blocks and coated with cement and brown plaster. It was constructed without roof or wall insulation and with single glazed windows and 45.83% window to wall ratio. The type of mechanical ventilation operated in the house was split unit AC and AC window units along, with a standing fan for air flow in the living room. The AC units were not maintained very often being only cleaned once a year.

The family, who lived in the apartment consisted of two adults and one child. This family was classified within the mid-income household group in this study, with annual income is between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were the house renter and his wife. They were both teachers in their thirties and slightly overweight. They both preferred to spend most of their time at home in the living room watching TV and were both dissatisfied with the design of the flat, as they complained about the hardly used huge guest area, as well as the western entrance to the living room, which, they stated, 'interrupts the privacy sometimes'.

The indoor physical measurements were collected from the living room, which was situated in the middle of the flat, without any source of natural ventilation, as seen Figure 6.46, and from the south-easterly facing bedroom. It is clear from Figure 6.47 that the thermal performance in the flat fluctuated around an average indoor temperature of 30ºC and 24ºC in the living room and the bedroom respectively. It is clear that the temperature in the living room was warmer than the bedroom by an average of six degrees, which might be related to the fact of being on the top floor with uninsulated roof. Therefore, the occupant uses the standing fan to circulate the air in this room.

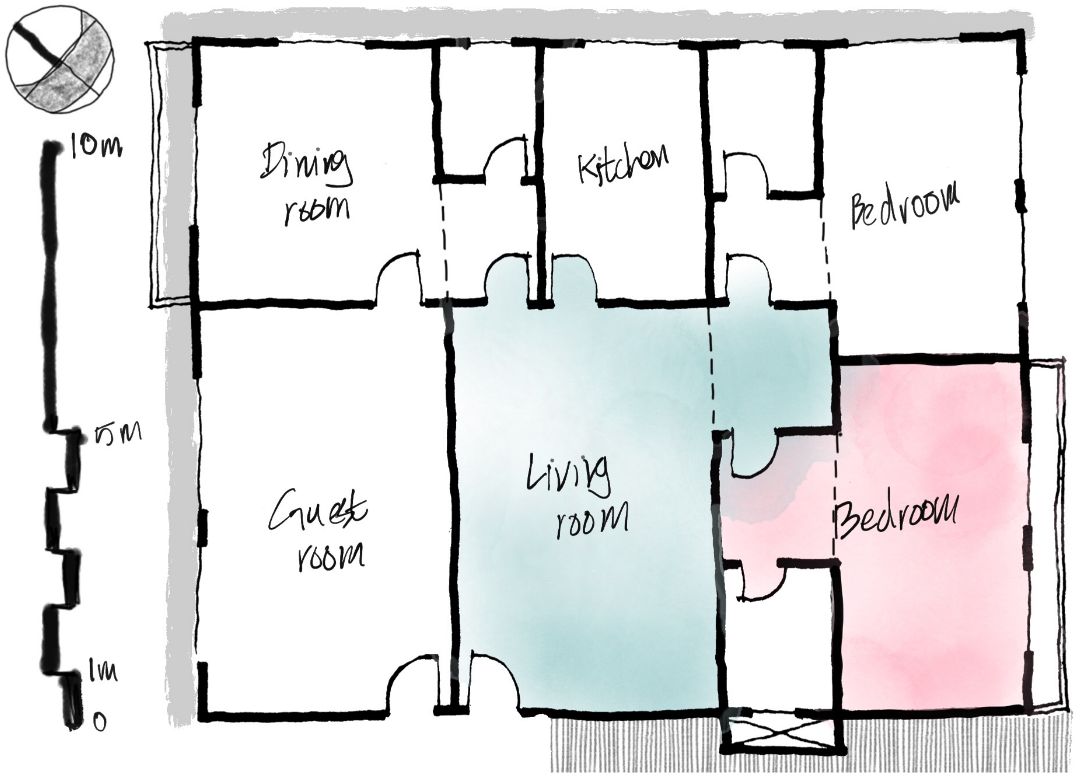


Figure 6.46 The design layout of dwelling #8

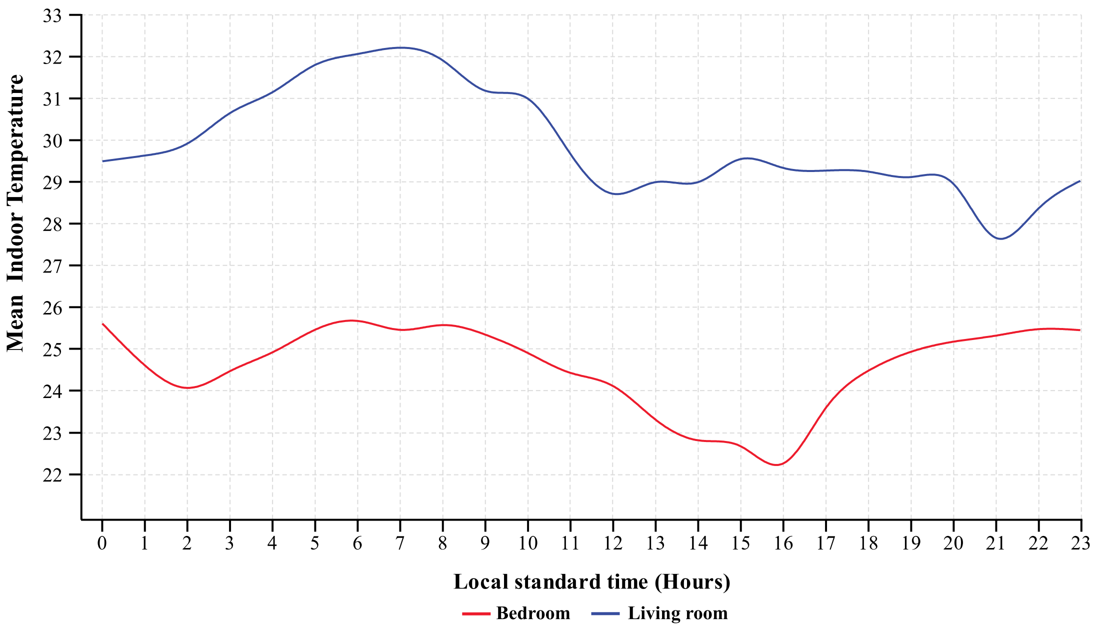


Figure 6.47 The performance of the average indoor temperature of the bedroom and the living room of dwelling #8 in the hot season within a 24-hour time series.

Figure 6.48 shows in detail how the indoor environment of the flat behaved in relation to the outside climate. Although it is hard to tell the history of this property, it is obvious that it was built with highly thermally conductive materials and that being under an exposed, uninsulated roof had a major effect. It is also evident that the occupants operated each room's AC only when it was occupied. However, the flat appears to be around 3K warmer than expected between midnight and midday, even though there was no sign of external conditions influencing the internal temperature while the AC was operating. In the bedroom, for example, when the AC was switched on before going to bed at midnight, the temperature slowly decreased to about 22ºC and remained at this temperature until midday, apart from a 2K temperature rise at 2am until sunrise. Subsequently, when they switched the AC off, the temperature increased to around 29ºC. Conversely, the temperature in the lounge was continuously warm and never moved below 27ºC, apart from one exceptional night, 27th of August (Figure 6.48), when the outdoor temperature of the previous day was the lowest for that week. Although there was no solar radiation directed on the lounge, the warm temperature was related to the large area of hot roof. Moreover, locating the living room internally without any access for natural ventilation has, in this case, blighted the liveable space, which is apparently allowed to free-float overnight to well above 30ºC and then to be cooled rapidly by AC. The humidity in both rooms fluctuated between 55% and 82% relative humidity with an average of 64.8% RH. In fact, the bedroom appeared more humid than the living room, especially before midnight, which may be attributed to the activity in the rooms.

Using the ASHRAE sensation scale, Figure 6.49 shows the occupants' thermal perceptions towards the indoor temperature. The householders responded slightly warm, neutral and slightly cool for almost all conditions in both rooms. Moreover, the occupants seemed to be satisfied with the indoor temperature, as they never responded warm or over in the hot season, and the choices of only 36% of the whole reported responses were slightly warm. In fact, the female was very sensitive to warm temperatures as she chose slightly warm with temperatures which ranged between 25ºC to 29ºC, whereas the male only selected slightly warm when the temperature was 30ºC or over. Those choices could be related to the activity of the subjects, as well as the associated time of voting. What was interesting was that the male responded neutral in the living room on the 27th of August afternoon at a temperature of 26ºC, whereas three hours later he responded cold at the same temperature. The female also did the same thing in the bedroom, with responses from slightly warm to slightly cool associated with the same temperature. The reasons for these responses could be related to taking the survey just after a nap, when the metabolic rate was reduced. In terms of temperature preferences, the male occupant would have preferred to have more cooling in both rooms. This preference was voted by the occupant who was usually outside the house, so the effect of the outdoor conditions on that occupant may have influenced this vote.

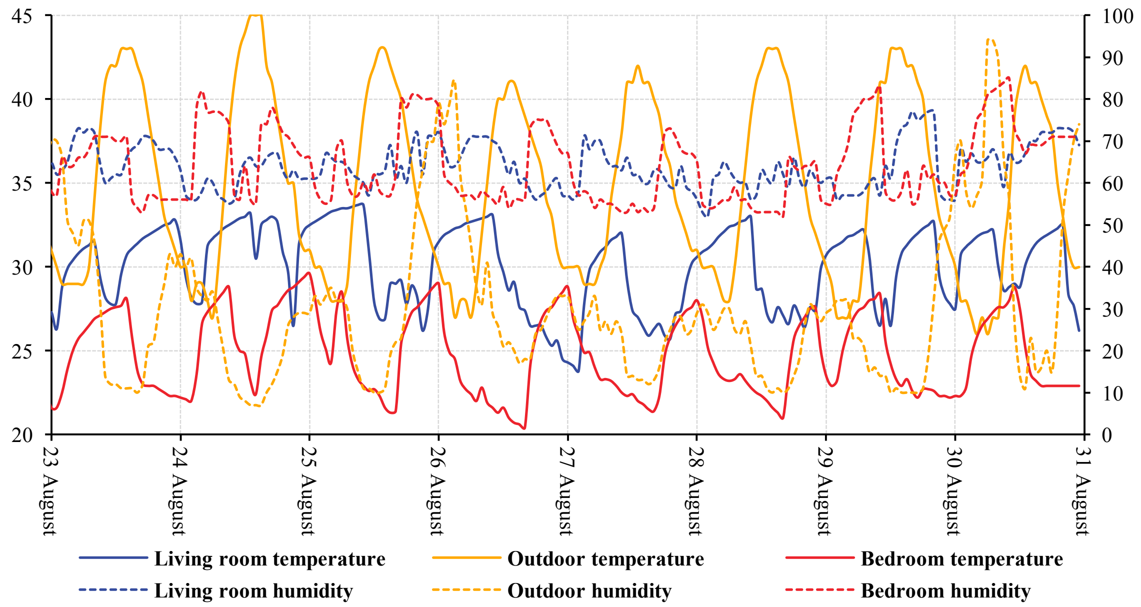


Figure 6.48 Plot of physical measurements of bedroom and living room of dwelling #8 along with outdoor conditions during the study period in the hot season

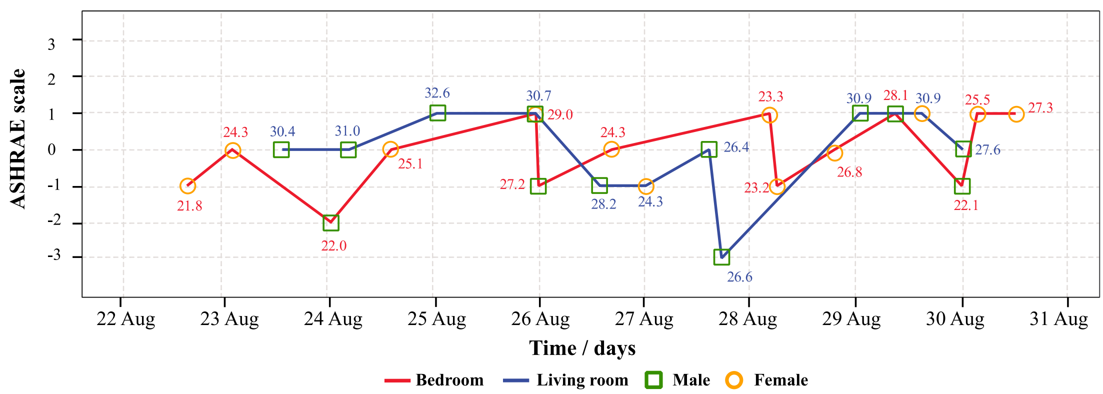


Figure 6.49 Scattering by gender and place of ASHRAE sensation votes in a multiple time series with annotation of indoor temperature in dwelling #8 during the hot season

Regarding the amount of the electricity consumed, the householder stated that they start to operate the AC system from April and do so until the end of September over both day and night-time. Figure 6.50 shows that the energy bill during August 2013 was 164.4 SAR (£29.9) for a total of 2,277 kW/h electricity consumed. The annual energy bill in 2013 was 1,220 SAR (£221.8) for 19,898 kWh electricity consumed, and due to the low monthly consumption there will be no change to the cost under the new electricity tariff. The amount of energy consumed in this flat is thus calculated as 142.13 kWh/m^2 per annum with the share per person of around 6,632.6 kWh per capita per annum.

Overall, the operational cost of the cooling system for the five cooled rooms flat, including the cost of the electricity bill and the cost of the AC system maintenance, which is 1,500 SAR (£272.75) for a single maintenance visit, was around 4,079.66 SAR (£741.7) per annum.

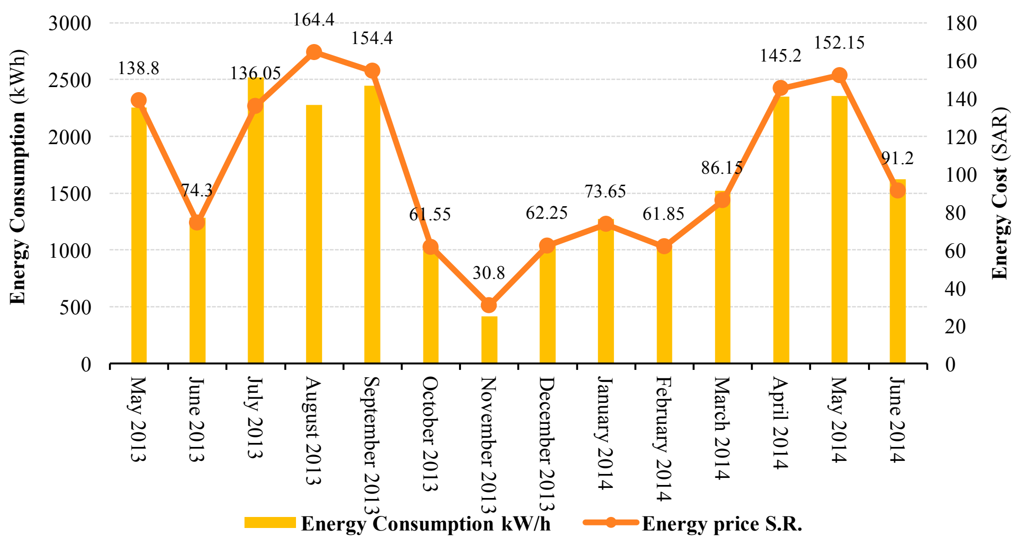


Figure 6.50 Illustration of an example of the energy consumption of dwelling #8 along with the price of the electricity bill.

6.5.2 *Dwelling #11*

This two storey detached house is located in Al-Jameyien neighbourhood and is 3100m away from the seashore to the east. The size of the house is about 800m^2, with a southeast orientation and located at the street corner and it was constructed in or after 2000. It was built of 20cm hollow concrete blocks and coated with cement and light pink colour plaster on all sides, without wall or roof insulation and with single glazed windows. The type of mechanical ventilation operated in the house was split unit AC along with the use of fans in some part of the house. The split units were not maintained very often, being only cleaned once a year. The occupants commented that having further insulation added in this big building would be expensive.

The family who lived in the house consisted of ten adults and one child: a father and mother, five adult sons and one daughter, with two housekeepers and a driver. This family is classified within the high-income household group in this study with annual income between 220 to 440 thousand SAR (£40-80 thousand). The subjects who were involved in the study were the house owner and his wife. They were in their fifties and both heavily overweight. As the husband worked as a medical consultant at the Ministry of Health, he spent less than ten hours a day in the house, while his wife was in the house most of the day. They both preferred to spend most of their home time in the bedroom section, as it was large enough and comfortable. However, they both disliked being in the living room, as it was a large space open to three corridors and has no upper floor, so the indoor temperature was relatively high. The husband was strongly dissatisfied with the design of the house, as there was a lot of wasted space in the rooms, particularly in the big living room, which was open between the two floors and could not cooled by the AC units. Unfortunately, the researcher did not get the chance to draw the house plan, due to a miscommunication with the householders after the survey's completion.

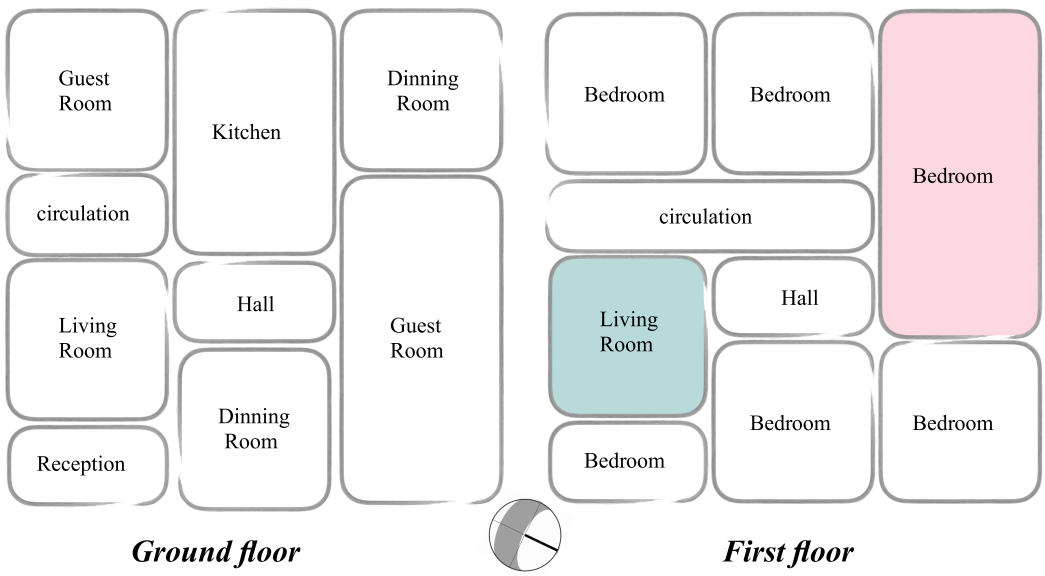


Figure 6.51 Basic zoning of dwelling #11

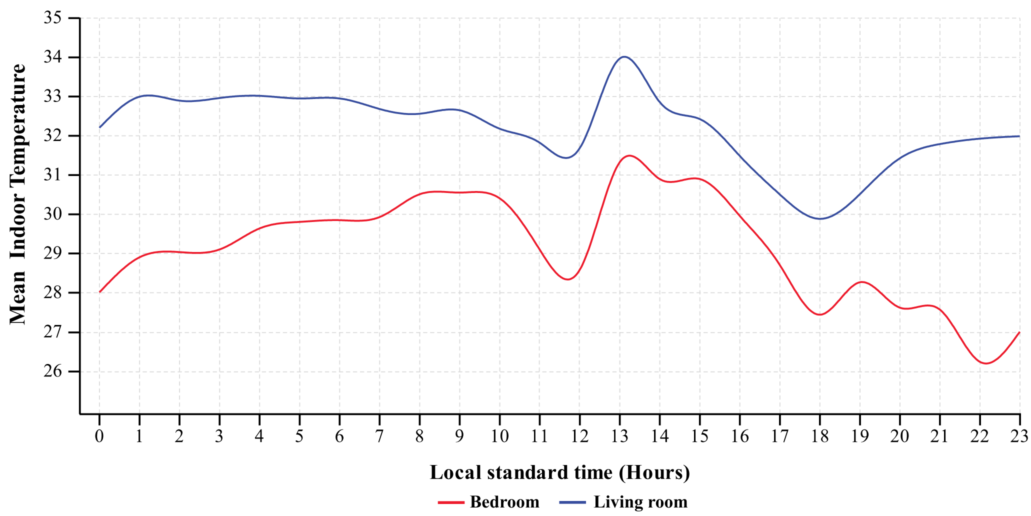


Figure 6.52 The performance of the average indoor temperature of the bedroom and the living room of dwelling #11 in the hot season within a 24-hour time series.

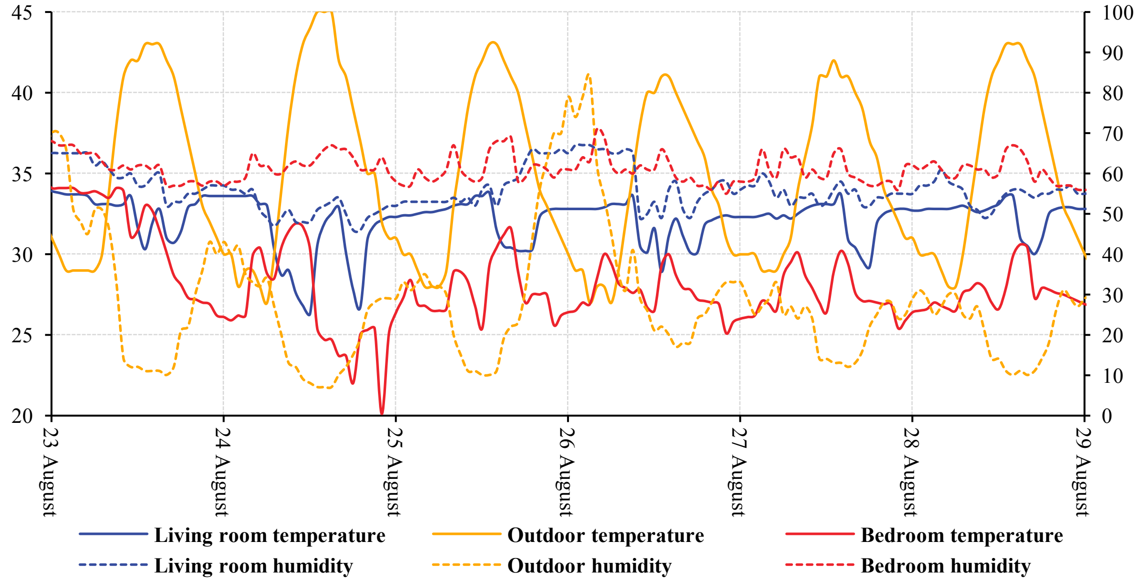


Figure 6.53 Plot of physical measurements of bedroom and living room of dwelling #11, along with outdoor conditions during the study period in the hot season

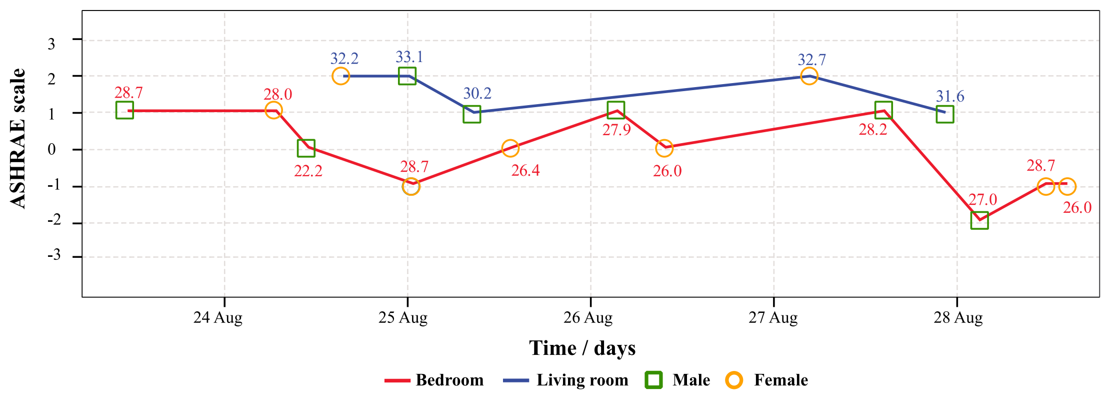


Figure 6.54 Scatter by gender and place of ASHRAE sensation votes in a multiple time series with annotation of indoor temperature in dwelling #11 during the hot season

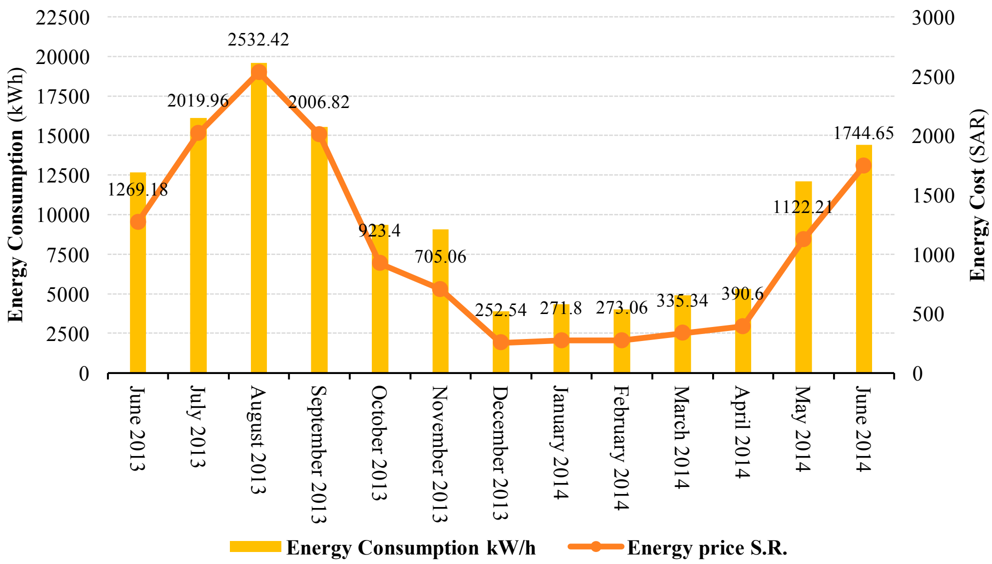


Figure 6.55 Illustration of an example of the energy consumption of dwelling #11along with the cost of the electricity bill

The indoor physical measurements were collected from the south-easterly facing living room and the west and northwest facing bedroom, according to the questionnaire information. Due to lack of assistant, it was difficult to get the measurements of the dwelling, so a basic zoning of spaces illustrated in Figure 6.51. It is clear from Figure 6.52 that the thermal performance in the house fluctuated around an average indoor temperature of over 29ºC during most of the day. Figure 6.53 shows in detail how the indoor environment of the house behaved in relation to the outside climate. It is obvious that the bedroom was running at ~ 5K colder than the living room. It is also evident that the occupants operated the AC only when it was occupied. It is apparent that the occupants were impacted on by the outdoor temperature. An example of this can be seen in Figure 6.53:when the outside temperature jumped to over 45ºC on the 24^{th} of August, the living room temperature fell to 25.4ºC, while the bedroom was at 20ºC, as if it were an extraordinary day. This lower temperature never occurred again, as the living room never ran below 29ºC and the bedroom was never below 25ºC. The humidity in both rooms fluctuated between 50% and 70% relative humidity. In fact, the lounge seems less humid than the bedroom, which might be because it was less used in comparison with the bedroom.

Figure 6.54 shows the occupants' thermal perceptions towards the indoor temperature according to the ASHRAE sensation scale responses. As the indoor temperatures of the bedroom were cooler than those of the living room, the householder's votes were registered as mostly on neutral in the bedroom and warm in the living room. In the living room, where at high temperatures over 30ºC the votes were warm each time, apart from two votes of slightly warm, the preferences were to have more cooling. In the bedroom, however, the sensation votes fluctuated within the comfortable range of slightly warm, neutral and slightly cool with temperatures between 22.2ºC and 28.7ºC. Moreover, the AC was operating almost all the time and the only adaptation was limited to the use of fan and opening the doors into uncooled spaces, distributed as 35% for each form of adaptation.

Regarding the amount of the electricity consumed in the house, the householder stated that they operate the AC from May until the end of October, over the daytime and from June until September over night-time. Figure 6.55 shows that the energy bill during August 2013 was 2,532.4 SAR (£460.4) for a total of 19,584 kW/h electricity consumption. The annual energy bill in 2013 was 12,578 Saudi Riyals (£2,286.9) for a total electricity consumption of 118,656 kWh. Consequently, the amount of energy consumed in this house was 148.32 kWh/m^2 per annum and the share per person was around 10,787 kWh per capita per annum. However, with the new electricity tariff, the annual electricity bill could reach 20,124.57 SAR (£3,659) per annum.

The total operational cost of the cooling system for the nine cooled rooms in this house, including the cost of the electricity bill and the cost of the AC system maintenance, which is 2700 SAR (£490.9) for a single maintenance visit, was around 16,628.2 SAR (£3,023.3) per annum. However, with the new electricity tariff, the annual operational cost could reach up to 24,175 SAR (£4,395), without the cost of replacement of any faulty parts during maintenance.

6.5.3 *Dwelling #15*

This two storey detached house was located in Qurtoba neighbourhood, ~2900m away from the seashore to the east. The size of the house was 450m^2, oriented towards the west and it was constructed in the eighties. Figure 6.56 shows the design layout of the dwelling, which was built of 20cm hollow concrete blocks and coated with cement and white and grey coloured plaster on all elevations. It was built without roof or wall insulation and with single glazed windows and with a huge window to wall ratio of 48.65%. The type of mechanical ventilation operated in the house was AC window units and split unit AC. The AC units were regularly maintained, as it became faulty very often, as well as cleaning it when necessary.

The family who lived in the house consisted of five adults, one child and a housemaid. This family was classified within the mid-income household group in this study, with annual income between 110 to 220 thousand SAR (£20-40 thousand). The subjects involved in the study were the house owner and his wife. They were in their sixties and both overweight. As the husband worked as an accountant at a retail company, he spent most of the day at work while his wife was in the house. They both preferred to spend most of their time at home in the living room, as it was big enough for all the occupants to watch TV. However, the occupants were both strongly dissatisfied with the design of the apartment as well as the thermal conditions experienced in their home.

The indoor physical measurements were collected from the east facing living room and the west and north facing bedroom. It is clear from Figure 6.57 that the thermal performance in the house fluctuated dramatically around an average indoor temperature of over 30ºC during most of the day. Figure 6.58 shows in detail how the indoor environment of the house behaved in relation to the outside climate. It is apparent that the dwelling was poorly insulated and built with highly conductive materials. It is also evident that the occupants operated the AC in rooms only when these were occupied. It is clear that the temperature of the living room was warmer than that of the bedroom. Moreover, the temperature in the lounge seemed to be constantly unsettled, fluctuating in the range of 29ºC to 34ºC. Despite this range of temperatures, on one unique night, when the maximum outdoor temperature on the previous day was 39ºC, the living room temperature was as low as 25ºC. The internal bedroom temperature in the afternoon jumped once the solar radiation hit the west wall. After sunset the temperature then gradually fell until midday. The humidity in both rooms fluctuated between 50% and 70% relative humidity and the lounge appeared to be more humid than the bedroom, which might be because it was close to the kitchen and open to all other parts of the house.

Figure 6.56 The design layout of dwelling #15

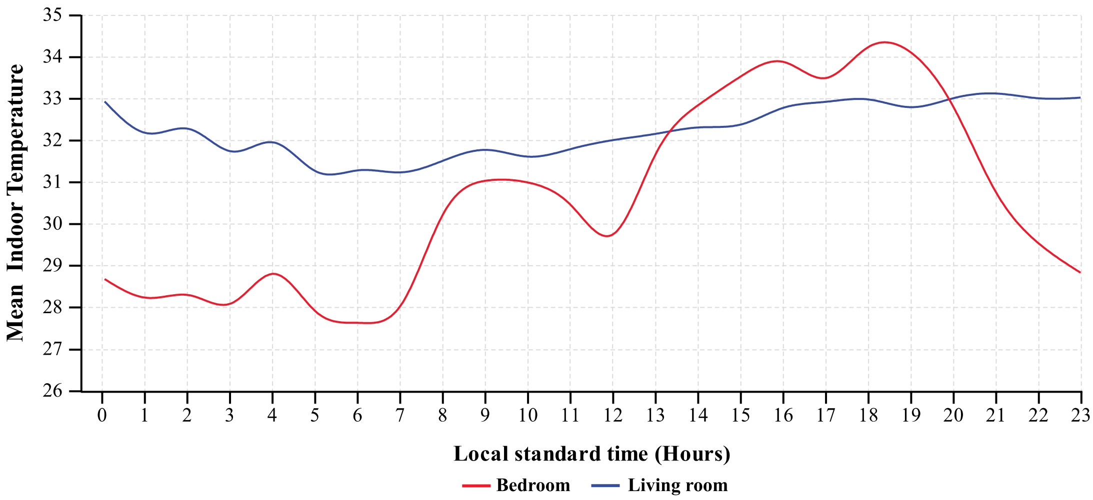


Figure 6.57 The performance of the average indoor temperature of the bedroom and the living room of dwelling #15 in the hot season within a 24 hour time series.

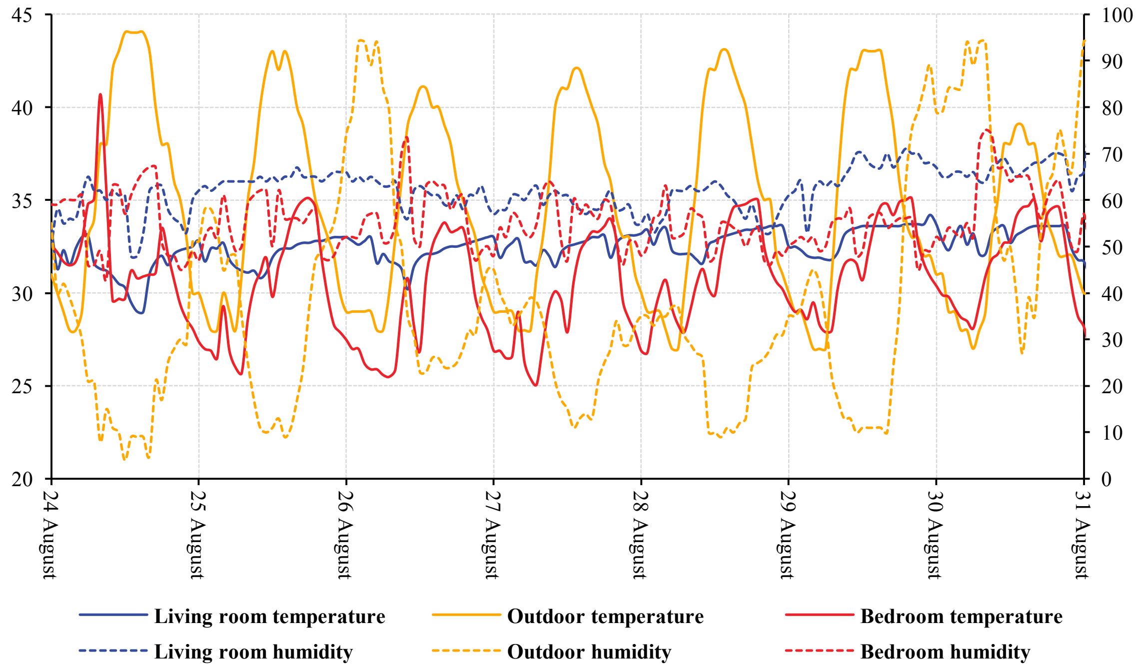


Figure 6.58 Plot of physical measurements of bedroom and living room of dwelling #15 along with outdoor conditions during the study period in the hot season

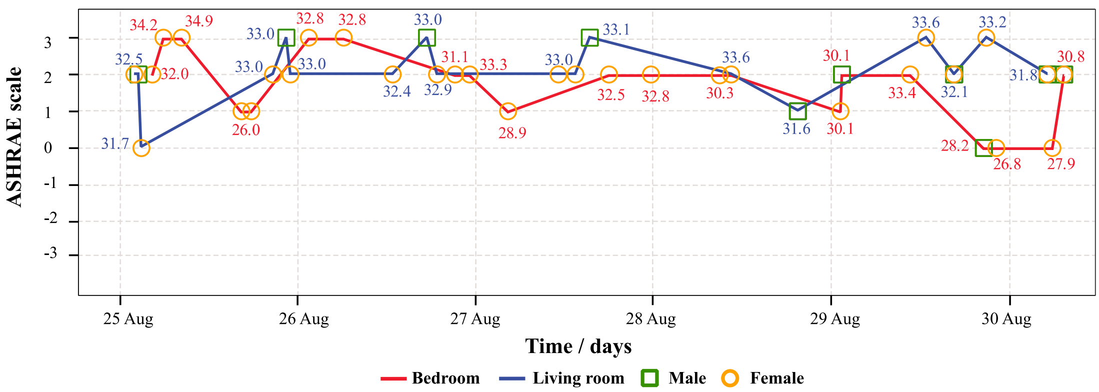


Figure 6.59 Scatter by gender and place of ASHRAE sensation votes in a multiple time series with annotation of indoor temperature in dwelling #15 during the hot season

Figure 6.59 shows the occupants' thermal perception in relation to the indoor temperature according to the ASHRAE sensation scale. It is obvious that the occupants were extremely dissatisfied with the indoor climate as they only responded on the warm side of the scale. The occupants only responded four and five times for neutral and slightly warm respectively, whereas the rest of thirty-two responses were warm and hot, concurrent with temperatures of over 30ºC. Moreover, the occupants continually indicated that they preferred to have much cooler conditions in both rooms because the indoor temperature was unacceptably warm nearly all the time. Interestingly, only around 4% of the occupants' responses indicated that they opened the windows while 58% of their total responses indicated that they opened the internal door into uncooled indoor space during the hot season. This behaviour must indeed account for the fact that the indoor temperatures were at some points less comfortable than the outdoor conditions. However, the occupants stated that they would pay more money to cool the house and get satisfied.

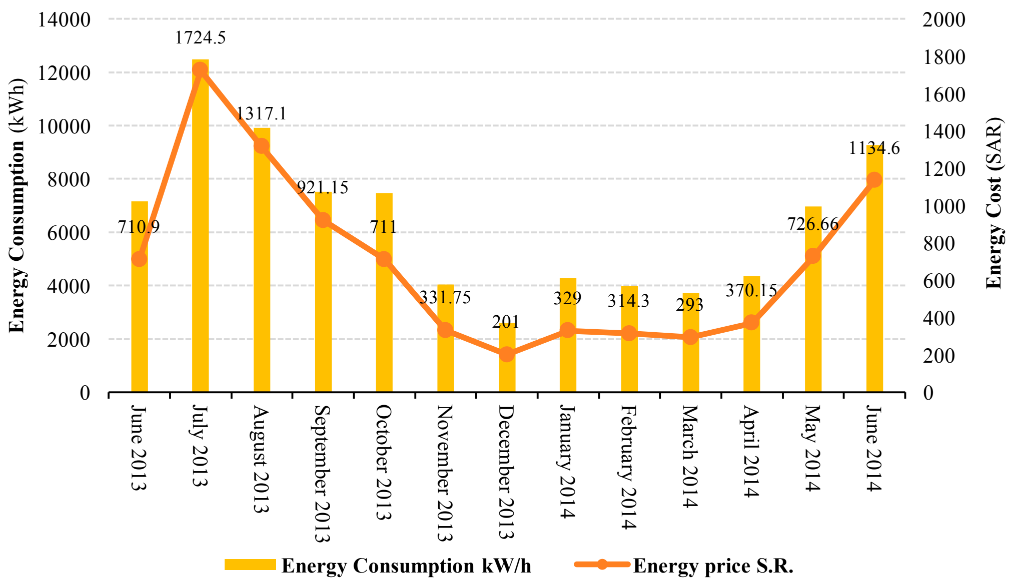


Figure 6.60 Illustration of an example of the energy consumption of dwelling #15 along with the cost of the electricity bill

Regarding the amount of the electrical consumption, the householder stated that they operated the AC from May and until the end of October over the day and night-time. Figure 6.60 shows that the energy bill during August 2013 was 1,317 SAR (£239.5) for a total of 9,920 kW/h electricity consumption while the annual energy bill in 2013 was 8,375 SAR (£1522.7) for 76,640 kWh electricity consumption. This means the annual electricity bill could reach 13,398.7 SAR (£2,436) per annum due to the new electricity tariff. Overall, the cost of energy in this house is 206.48 kWh/m^2 per annum and the share per person is ~10,948.6 kWh per capita per annum.

Additionally, the operational cost of the cooling system for the seven cooled rooms in this house, including the cost of the electricity bill and the cost of the AC system maintenance (2,100 SAR (£381.85) for a single maintenance visit) was around 11,524 SAR (£2,095) per annum. However, with the new electricity tariff, the annual operational cost could reach up to 16,549 SAR (£3,009), excluding the cost of replacement of any faulty parts during maintenance.

6.5.4 *Cluster C: Conclusions*

Although these three dwellings varied in terms of orientation and size, they had common characteristics. They were all uninsulated, had erratic indoor climates, and consumed more than 140kWh/m^2 per annum. Flat #8, for example, consumed about 142.13Wh/m^2 per annum, even though it appeared to be reasonably well-oriented. It is thus clear that the design of the flat and the construction materials of the apartment were poor. The position of the apartment on the top floor increased its exposure to heat ingress and the bad quality of the mechanical ventilation provision in the dwelling must also have influenced the indoor climate and increased energy consumption. Furthermore, house #11 consumes an enormous amount of electricity of 148.32kWh/m^2 per annum just to achieve a mean indoor temperature of 28.6°C. This amount of energy consumption achieves only warm indoor conditions, as a consequence of the orientation of the house, bad design of the living room as well as its inefficient mechanical ventilation system. Moreover, house #15 appears to perform even worse: with a mean indoor temperature of 31.5°C, it consumes a massive amount of electricity of 206.48kWh/m^2 per annum. This example is the most unsatisfactory of all the homes in the study, suffering from poor indoor climates, with orientation to the west, no insulation and an inefficient mechanical ventilation system. These factors undoubtedly influence the dissatisfaction of the occupants expressed in their ASHRAE scale votes, with a mean of 1.8, warm, on the scale.

6.6 Summary

The main points that can be drawn from this chapter were that the people whose costs were less per m^2 were those who fairly often feel neutral and slightly cool in the sensation scale and conversely those who paid more for their energy reported in fact being less comfortable. Moreover, the type of insulation and surface finish coating on the property creating the dwellings envelope has a clear influence on energy demand

and consequently the costs of bills. In some cases, furthermore, a good quality of AC system, with regular maintenance, reduces the likelihood of higher energy demand. Last but not least, both the orientation, as well as the window to wall ratio of each dwelling, have an enormous impact on the thermal experience within the dwellings and therefore influence on the energy demands for cooling. Therefore, in the next chapter the substantial design and adaptive opportunities available in these dwellings that, in turn, affect the thermal conditions experienced, as well as the energy consumed in each household, are discussed. The criteria for the well and badly performing homes will be defined, based on the energy consumed in each case per square metre, kWh/m^2, allowing for the rating of the properties into low and high energy consumption examples.

CHAPTER SEVEN: DISCUSSION

"The whole is greater than the sum of the parts"

Kurt Koffka

7.1 Introduction

The results of the present study found that the comfort temperatures reported by Dammam's residents in their own homes ranged between 19.2°C and 35.8°C which support the use of adaptive thermal methods in this study. Around 70% of subjects were likely to be comfortable at a neutral temperature of 25.8°C. The study indicated that at this temperature all subjects would be comfortable, reporting "neutral" on the ASHRAE sensation scale and "no change" on the preference scale. However, Dammam's outdoor air temperatures range between 26°C and 47°C, presenting at times real challenges, both for housing designers and occupants, to provide indoor thermal comfort with a number of different strategies to hand, including building design, mechanical systems and behaviours, all of which were investigated in this study. In this chapter, the results of those investigations in the previous chapters are discussed and related back to the following objectives of this thesis, as defined in chapter 4.

1. *What opportunities exist to improve comfort in the occupied dwellings in Dammam while not increasing energy use?*
2. *How do we make sense of the lessons learnt from the studied dwellings in order to give efficient and user-friendly guidance to design new homes in the region?*

Historically, low energy prices in Saudi Arabia encouraged users not to restrict their use of energy on the grounds of costs. The combination of a lack of awareness of the environmental impacts of energy use and the many social pressures to pursue an energy-intensive lifestyle mean that energy demand is extremely high in the region. Therefore, when asked the occupants about their electricity bills, and more than the half of the participants replied that they often have high bills during summertime that ranged between £90 to over £200 per month taking the fact that the cost of a kWh of electricity delivered to the householder is ranging from only a penny to 29p for the highest consumer. However, in December 2015, the prices of domestic energy were increased overnight by 60% for those high-end consumers who paid more than £600 per annum for their energy bills. Thus, the cost of occupying low-performance dwellings is soaring for many, making this a good time to introduce guidelines to implement a step-change in the design and refurbishment of homes in Dammam for improved thermal performance.

The information gathered in the preceding chapters has demonstrated that achieving thermal comfort in Dammam's existing dwellings with the least possible energy consumption is a complex, if not "wicked", problem. In order to provide robust and useful guidance on how to improve performance, it is necessary not only to describe the opportunities available but to also evaluate the effectiveness of those opportunities in practice. The following discussions explore the strengths and weaknesses of the physical, behavioural and attitudinal opportunities identified in the homes in the study and the efficacy of each one. The conclusions from those discussions cover lessons learnt from the studied dwellings in relation to design for affordable comfort, which may be applied retroactively to existing homes as well as to the design of new buildings.

7.2 Dwelling's design opportunities

One of the most effective strategies for reducing domestic energy consumption is to optimally design the building envelope to reduce over-heating in the home, which leads to excessive energy consumption for cooling. A high-performance dwelling envelope can increase the occupants' comfort and well-being. The building envelope is a major factor in determining how much energy will be needed for cooling and lighting the dwelling. Designing a dwelling with non-integrated characteristics, when the design elements are not linked with each other as one project (like in dwellings 3, 4, 5, 7, 10, 12, 14, 16 and 17), clearly leads to sub-optimal results. While individual design characteristics can have a significant effect on energy, achieving both comfort and low consumption often requires 'whole system thinking', as it is the sum of many different building and behavioural attributes which contribute to an indoor thermal environment and the cost of maintaining it. The individual attributes listed here are discussed below individually and as clusters in the case study houses:

1. Optimum orientation
2. Adequate internal space arrangement
3. Appropriate allocation and sizing of fenestration
4. Appropriate daylighting and shading
5. Ideal cooling and ventilation strategies
6. Efficient energy construction.

7.2.1 *Orientation*

It is noted that there is not even a mention of designing with the proper orientation in the Saudi architectural design criteria and buildings code (SBCNC, 2007). The findings of this research therefore indicate the need for a major overhaul of the Saudi construction standards and building codes to take into account the basic issues of optimal energy performance and also the comfort in dwellings. In the extremely hot climate of the Dammam region (location: 26° 19’ N, 50° 08’ E), the northern orientation of windows typically results in cooler indoor conditions, due to minimisation of incoming incident solar radiation from that direction. An easterly orientation can also result in cooler temperatures indoors, as solar gain through the building coincides with cooler outdoor temperatures. Southerly and mainly westerly facing windows allow heating gain from the mid-afternoon, evening and setting sun, at a time of day that coincides with the hottest external temperatures, consequently causing overheating of adjacent rooms in dwellings to build up gradually from noon onwards, making the west typically the most uncomfortable orientation in Dammam’s homes.

Most of the dwellings in this study appear to have been oriented with little or no consideration of orientation or attention to the wind direction, solar radiation or the thermal context of the local micro-climate. Consequently, a range of more or less unpleasant environments have been created inside these homes. The implementation of inadequate orientation of these dwellings is necessarily also a result of how the local planners originally oriented the streets they are located in, paying little heed to the local climatic design conditions and the impact of their own planning choices on comfort in the resulting homes. Mosques are recognised as one of the fundamental planning features within Islamic cities, and as mosques should be oriented to Makkah for prayer direction, planners have oriented most streets towards the direction of Makkah (in the case of Dammam, West-Southwest 245° from the north) in order to ease the Qiblah direction for people. In most neighbourhoods, the Mosque's orientation towards Makkah affected the orientation of the surrounding streets, because, on the whole, dwellings in this region take the same direction as the streets. In the dwellings in this study, six out of the nine available homes’ plans, are oriented with the longer façade facing Makkah, which means they are likely to have inferior conditions, as this extends its exposure to the harshness of the western sun.

It is clear from the seventeen dwellings investigated in this study that the orientation of the dwelling plays a massive part of the dwelling’s energy consumption. Not surprisingly, two of the highest performing dwellings in this study are oriented with their longer façade facing the northeast, with around 90 kWh/m^2 energy consumption per annum. However, six out of the seven most energy-intensive dwellings in this study are improperly oriented, with the annual consumption of these homes ranging from 118 kWh/m^2 to a maximum of 206 kWh/m^2 per annum.

Proper orientation demonstrably enhances a dwelling's indoor climate: for well-performing dwellings', as in numbers nine, the orientation of the longer façade of the dwelling has a tremendous impact on the mean indoor temperatures, and the average daily temperatures of this dwelling was below the comfort temperature. All dwellings that were properly oriented with their bedroom windows facing between north and east had average daily temperatures of less than 25°C, apart from house number six, where the preference of the occupant was to occupy warmer conditions. On the other hand, when a dwelling was improperly oriented, with its bedroom windows facing west, as in cases thirteen and fifteen, the indoor temperatures exceeded the comfort temperature by at least 3K. In the cases where the west side of the bedroom was blocked by a solid wall and its windows opened to the south, as in dwellings eight and twelve, the average daily temperatures in those bedrooms were 24°C and 22°C respectively.

Furthermore, nearly of all the occupants who were living in well-oriented homes reported being very satisfied with the overall thermal environment. Conversely, the level of satisfaction with thermal conditions for those occupants who lived in poorly-oriented dwellings was slightly lower, unless other major factors and influences masked the weakness of the dwelling's orientation.

From this study it was found that the best solar orientation was achieved when the longer dimensions of the dwellings faced north and south, as these two elevations receive the least direct solar radiation. East and west elevations receive almost the same amount of sunlight, but in the afternoon air temperatures reach their highest peak and the heat load increases greatly. Therefore, it is important to choose the dwelling's location within the street carefully, with the longer façade oriented to the north/south and fewer openings on the other façades.

7.2.2 *Internal space arrangement*

The design of the dwelling's envelope is directly connected to the internal layout and room arrangements that fundamentally affect the heat distribution within the spaces in the home. Internal space planning responds to both the climate and the local site conditions, where space buffering, or its lack, is generally seen as a factor strongly related to increasing or reducing heat gain through the envelope. As a consequence of the absence of space buffering, it appears that this decreases the degree of comfort and perhaps extends the operation of the cooling load, which increases the operational costs.

As the western façade is likely to receive maximum radiation at the hottest time of day, all spaces adjoining this façade will experience the maximum heat gain. It is apparent from case number six, as an example of a semi-open plan ground floor, that the heat gained from the western façade fundamentally affects the interior temperatures, as the heart of the home was never below 31°C. Therefore, it is recommended to design the internal layout of the dwelling in such a way that most of the regularly occupied spaces are placed along the northern or southern façades and away from the western façades. The less occupied spaces, such as storage and service areas like toilets, staircases and so on, should be used as buffer spaces and allocated along critical orientations lying west, east, south-west and southeast.

In this study, the deliberate use of thermal buffering spaces was found to be limited and, in fact, in some cases misused. Dwelling number thirteen, for example, has a massive entrance into the guest area that also works as a buffer space oriented to the north, with the main bedroom lying to the west, with a mean internal temperature in the evening in this room above 30°C. In case number eight, where the hardly used guest area is also lying to the north, the living room directly opens on to the western entrance hall, and consequently, the internal temperature here was always higher than 28°C.

On the other hand, apartment number nine uses the buffer space adequately, with a reasonable internal layout. The closed hall space in the outdoor entrance buffers the guest room and the living room, and the location of the least used guest room is to the south, leaving all the main bedrooms to the north, which has worked perfectly. Placing the lounge in the middle of this apartment reduced discomfort, as it limited the heat gain to the most used room. However, this arrangement did limit, to some extent, the use of natural light and ventilation in this living area; however, they could, to some extent, compensate for this by opening the eastern window in the kitchen. Another good example is in the living room of case number twelve, which benefits from the bedrooms buffering it, leaving the mean temperature continually stable at around 25°C. Similarly, in case number eight, the bedroom takes advantage from the living room position as a buffer zone, and the temperature in it was always 4K less than in the living room.

It is also important to buffer the roof membrane against the harsh effect of the direct sun. A well-ventilated roof space and the inclusion of non-habitable spaces in the attic plays a critical role in some dwellings in passively cooling rooms by providing a thermal buffer zone between internal and external spaces. In dwellings six, nine and five, for example, the owners pointed out 'that the dwelling's ceiling is entirely covered by suspended ceiling concealing the ducts, piping and HVAC system'. The use of a suspended ceiling allows the hot air to flow to the upper buffer zone between the ceiling and roof, which reduces the temperature differential across the ceiling insulation. Conversely, in cases three, eight, eleven, thirteen and fifteen, where the dwellings do not have roof insulation or suspended ceilings, rooms are exposed to the harshness of the direct sun from the top. Accordingly, the indoor conditions, as well as the cooling energy demand, became a misfortune. Therefore, it is important that rooms benefit from the use of such a roof buffer, not only to protect against the ingress of incoming radiation, but also to form a trap for the hot air rising from the room below.

A closer study of the design and room arrangements shows that there are a lot of wasted areas in most homes. It is clear that people have little understanding of the thermal and energy implications of room location and zoning. People lend more weight to the value of privacy and 'making a show' in front of their guests, rather than valuing their own comfort, wellbeing and energy economy in their own homes. In most of the dwellings in the current study, the *majlis,* or guest reception room, was hardly used throughout the year, but its size and location significantly affected the internal layout and orientation of the rooms in the home, being treated as a priority to be displayed prominently to guests. During the informal interview with an occupant of dwelling number nine, he said: *"if I had the opportunity to redesign this flat, I would rather have a bigger living room instead of a huge, rarely used, guest room".* In house number six, half of the ground floor is taken up by the guest reception, and occupants there stated that *"it is barely used once quarterly, and we regularly invite our family guests in the living rooms as the cooling system needs more time to cool the majlis".* In dwellings number eight and thirteen, the guest sections take up the best location in the houses, oriented to the north, and bedrooms were then oriented to the west and south, significantly increasing energy needed for the cooling load of the lifestyles of those in the occupied rooms of the dwelling. When questioned about the poor thermal design of the rooms and the opportunities available to rearrange functions within the house, the occupants displayed no inclination to make the changes, as '*they got used to it'*. Therefore, prioritisation of the need to afford comfort for occupants themselves is a significant issue in the design of homes and needs more investigation and more education of new home-owners.

The above section indicates that a carefully differentiated spatial design should respond dependently to the microclimate within the home at each given site, which may contribute to the improvements in the comfort experienced and reductions in energy costs for occupants. This evidence shows the benefits of providing indoor living spaces that are screened, shaded and protected from outdoor heat. It also appears to be preferable to locate non-habitable rooms like toilets, stores and staircases on the east or west end of the home, so that they can act as a thermal barrier, which can have a significant influence on the indoor conditions and energy performance. Moreover, it seems to be necessary to locate living areas correctly in a thermally protected zone and situate bedrooms in sleeping comfort zones that, again, are highly insulated, shaded and well-sealed from the ingress of hot external air. This may be seasonably adjusted to take advantage of cooler summer places as well as warmer winter rooms. Using the roof ceiling void, furthermore, to create a buffer zone to contain and store rising heat from below and incoming heat from above appears also to be effective in improving indoor comfort and cooling demand. What is clear is that there is a common balance of choices being made in the homes as to whether they should be carefully designed in terms of their spatial planning for comfort and wellbeing or for their social impact on visitors, and the latter typically wins, in the end.

7.2.3 *Allocation and size of fenestrations*

In considering the orientation of the dwelling, the issue with most climatic impact is the orientation of the glazed openings. Traditionally, in many hot regions, openings in the external walls of buildings used to be limited in number and small in size, to reduce the impact of the extremely hot climate on indoor spaces. However, most of contemporary dwellings in the Dammam region seem to be designed with large window openings and with relatively little attention given to the local climate. Thus, without the use of mechanical cooling, an unpleasant internal environment is created with both direct and re-reflected solar incidence coming in through walls and windows.

Fenestrations should be carefully designed into dwelling facades to reduce the heat gain into the homes. It is always recommended to provide maximum openings along the northern façade and avoid openings on the eastern and western façades, to allow maximum daylight and minimum solar radiation to enter the dwelling. It appears, to some extent, in this study that the designers of most of the studied dwellings have paid little attention to the orientation of the openings in the design of these homes. In fact, in some cases, a window was placed in every possible wall inside the rooms, which may prove to be completely unnecessary. The bedroom's west window in both dwellings number thirteen and fifteen, for example, could have been just omitted to reduce the heat gain in these rooms. Moreover, in case number eight, where around a half of the façades incorporate single-glazed windows, the south-easterly oriented bedroom has two large windows, and consequently, the occupants are likely to operate the AC all the time, just to keep the temperature of the room tolerable. A good example of reducing the heat gain from the western side is seen in dwelling number twelve, where even though the bedroom has two windows to the east and the south, the temperature never exceeds 24°C, which may have enhanced the experience of thermal comfort reported by the occupants.

Windows typically have a higher conductance coefficient than the rest of the building envelope. Therefore, dwellings with a high glazing ratio have greater heat gain, compared to similar homes with a lower glazing ratio. Solar gain through large windows in summer can elevate a dwelling's indoor temperature well above the outdoor day or night temperature levels and thus cause intolerable conditions indoors and significant thermal stress, consequently increasing the building's cooling load to compensate for this poor design. In house number fifteen, for example, where the glazing ratio is around half of the façades, the indoor temperature is commonly higher than the outdoor temperature. There appears in this study to be a clear relationship between the amount of the window opening to wall ratio and energy consumption. The larger the window area is in the façade, the more intense the energy demand for cooling is in the dwellings. For instance, as the size of windows in homes one, five, six and nine is very reasonable, the consumption 90 -108 kWh/m^2 per annum, being the lowest average consumption of all the studied homes, whereas in dwellings three, eight and fifteen, where the ratio of window to façade wall area ranges between 31% to 49%, the energy consumption ranges between 125 and 206 kWh/m^2 per annum. Therefore, as one intuitively suspects, the homes with smaller areas of fenestration that are also well-oriented, provide much better protection against heat gain during the day.

The types of windows also have an impact on energy savings. Double glazing with low emissivity coatings or insulation appears to make a real difference. In the studied homes, the top four high-performance homes, as well as the seventh, were the only double-glazed dwellings in the study, whereas all other dwellings have single-glazed windows. In conclusion, it is clear to see that fewer, smaller, well-oriented and double glazed windows do all play a significant role in the thermal and energy performance of the dwelling.

7.2.4 *Daylight and shading*

It has commonly been assumed that daylight as a natural source of light can be used for the satisfactory illumination of rooms during the day. However, due to the adverse hot conditions from the intense internal heat and intolerable visual glare experienced in countries with a very hot climate like that in Saudi Arabia, not only does daylight have to be well managed when being introduced through fixed openings into the home, but adaptable shading used at different times of day and year is also important for thermal and visual comfort. Good façade design, fenestration and shading can considerably address the problem of glare and reduce the impact of high insolation, as well as being used to protect the visual privacy of occupants. Shading devices that are attached to external fenestration need to be optimised for their solar angle, so that the shading device can keep the summer direct sunlight out when required and allow the winter sunshine to enter the dwelling. However, as the western and eastern walls of a dwelling are difficult to shade at periods when the sun is at a lower angle, a vertical screen or shading methods would work best.

However, the current study found that occupants in the case study homes do not use external fenestration shading at all and rely solely on internal blinds and curtains to just screen the internal glare. One of the homes' occupants, in fact, has completely blocked the façade's windows with rolling aluminium shutters, to obstruct any contact with the outside. The occupant of dwelling number sixteen claimed that the reason behind the blocking is to reduce the amount of glare, as well as to prevent neighbours watching. Practically, there are various types of fixed façade-shading strategies that could be integrated into the dwellings' design instead of full blocking. These strategies include roof, wall, and window pergolas, false walls and screens, as well as *Mashrabiah, a* local tradition that used a ventilated timber structure superimposed over the external surface window to provide adequate shade, illumination, breeze and privacy.

Although not used in most of the case study homes, trees to the eastern and western sides of the house could create a cooler environment around the dwelling as an alternative shading strategy for the home. Although all homes in Saudi Arabia are surrounded by set-back spaces behind walls, creating front, side, and rear yards, which in some cases can be entertaining spaces, it appears that people do not have an interest in planting vegetation around their dwellings to provide shade. This may also be a reflection of concern about water shortages; however, plenty of grey water must be produced from showers etc., so new approaches to planting and shading may enhance the opportunities for new water recycling products in the local market. Nonetheless, with the hot climate of Dammam, people claim that it is always impossible and expensive to maintain gardens, and that they prove not to be usable for most of the year.

Some comments were made during the informal interviews conducted with dwelling occupants. One reason given for the residents not planting vegetation or using the yards is the small width of the yard (in most cases 2 metres wide on the four sides of the dwelling) which made them unsuitable for any activities except as semi-private walkways or storage areas. Some residents used the setback spaces for a further building extension, for example, to provide additional storage or an outdoor dirty kitchen, as was the case in dwelling number five. Another resident claimed a convincing reason that these setbacks provide an unpleasant environment is that "*the surrounding area is not big enough to plant and unsuitable for any habitable purpose, not to mention the lack of protection against the intense heat and harsh climates like dust and sandstorms*".

However, being in such an unpleasant environment should not prevent people from planting, as planting itself may make it much more pleasant. Taking the fact that the nature of most of the eastern province lands is saline moor soil, where agriculture is considered to be difficult, it is obviously necessary to find suitable planting solutions for the region. The occupant of dwelling number five had experience of planting the surrounding yards and said "*we planted 20m^2 of the front yard at a first stage. However, after a while we realised that it consumes too much money and effort as well as lots of water, not to mention the need for treatments against the harsh weather and insects. Therefore, we have decided to replace all plants with floor tiles".* The occupant of dwelling number six, in contrast, was very pleased with the planting and pergola he had completed in his house's yard and was very satisfied with the resulting outside environment. He said: *"we imported a particular type of soil from the nearby region and selected the plants very carefully as we want the environment to be clean and comfortable for my family whatever it cost us."* Therefore, with the right kind of soil and plants, and perhaps more importantly, with a sustainability-oriented user attitude, it is possible to grow plants properly for adequate passive shading of façades.

It is clear from this section that shading plays a significant role in the indoor temperature as well as the energy performance. It is important to permanently shade all walls and windows to exclude heat gain from accessing the home. Considering shading the whole dwelling, moreover, it may also be very useful to shade the outdoor areas around the home with shade structures and /or with planting, to lower the ground temperature, and hence, the temperature of the incoming air.

7.2.5 *Cooling and ventilation strategies*

Mechanical cooling for human comfort indoors is now considered essential in almost all of Saudi Arabia due to its extremely hot climate. Many people now totally insulate themselves from the climate in air-conditioned homes, instead of adjusting to local climatic conditions at any or all times of the year. It is very evident that the design of contemporary homes is increasingly predicated on relying on air-conditioning in controlling and regulating the indoor climate over the year. Nevertheless, efficient cooling and ventilation strategies in dwellings should engage a variety of cooling options (including air conditioning) in the most efficient and effective way. The dwelling's design, therefore, should take maximum advantage of passive cooling, when available, and make effective use of mechanical cooling systems, largely when most necessary, during extreme periods.

Although an efficient AC system is very expensive to install, operate and maintain, it appears in the current study that the AC system's level of inefficiency is generally assumed to play a role in the increment or reduction of cooling load and in return its energy cost. House number thirteen, for example, with the highest home energy consumption per square metre, paid an enormous amount, in Saudi terms, for its energy bill of £3.85/m^2 per annum. The occupants stated that they also spent an excessive amount of money maintaining the AC equipment, due to the fact of it being an inefficient type of AC system, set also in a poor house design. However, in dwelling number three, also a poor house design with roughly the same other contributors, the energy bill cost £2.10/m^2 per annum, as a result of a reasonably efficient AC system. Accordingly, it is likely that the cheaper energy cost is a result of an efficient AC system in a more highly-performing home. In dwellings number nine and one, the energy costs, for example, are £1.14/m^2 and £1.10/m^2 per annum, respectively. Taking into account the fact that these dwellings have among the top performance envelopes, these particular two homes also have efficient cooling systems that are regularly maintained with a maintenance contract.

Refrigerated air conditioning lowers both air temperature and humidity to a certain pre-selected level that provides thermal comfort during periods of high temperature and humidity. It is apparent that the US engineers had identified the 55% relative humidity as an optimal level of indoor relative humidity, even though this assumption was based ostensibly on little scientific evidence, especially for extreme hot humid climates (Huh and Brandemuehl, 2008). Consequently, to strive to deliver air at this locally low humidity at this optimum level, can be achieved only with an enormous amount of energy expenditure. As people do not like the feeling of sweat / moisture on their skin they might report humidity as being one of the leading causes of discomfort in hot climates. In this study, the indoor relative humidity experienced in the studied dwellings ranging between 23% to 96% relative humidity in both seasons, and the occupants did not report significant levels of resulting discomfort. In future studies it may be preferable to investigate more about the feeling of dampness or skin wetness and levels of air movement rather than asking occupants about their perception of humidity levels in an occupied room. It was also found that the majority of people felt comfortable at a higher rate of relative humidity than that which is assumed by the HVAC industry, with occupants reporting no humidity discomfort at levels above 55% Relative Humidity. Thus, it is essential to review the relevance of mechanical system specifications, mainly regarding the specified requirements for dehumidification of water vapour in the air in relation to what is actually reported as acceptable for the locally adapted population. More research is clearly needed concerning the relationship between temperature, humidity and comfort for the Gulf population and its impact on related standards adopted for regions with extreme climates such as the Gulf.

Since the indoor humidity in Dammam's dwellings reaches such high levels, combined with the high temperatures, the body's physiological might increase the ability to lose heat by evaporating perspiration. Sleeping discomfort is a significant issue, especially when the night temperatures remain above those required for human comfort. Running the AC system in a closed room for about an hour at bedtime often lowers the temperature as well as the humidity levels to the point where air movement from ceiling fans can provide sufficient evaporative cooling to achieve and maintain sleeping comfort. Standard ceiling fans can create a comfortable environment when temperature and relative humidity levels are within acceptable ranges. In house number six, for instance, the occupants were shutting down the air-conditioners for around 20 to 45 minutes every two hours in the day time, even when the indoor temperatures exceeded

29°C, and operating the ceiling fan. This house was subsequently able to achieve the highest performance and least energy demand per square metre among the studied homes. Furthermore, the operation of fans reduces the number of months of operating the AC system at night, when the outdoor temperature is tolerable with adequate air movement.

As air conditioning is commonly used to create comfortable conditions, the number of operating hours required to achieve thermal comfort can be substantially reduced by careful design of homes. It has been found that the air-conditioning in a poorly-designed dwelling (cases eight, eleven, thirteen and fifteen) with an inefficient AC system remains in operation for around nine months through the year, three more months of operating the air-conditioning than in well-designed dwellings with a good AC system. On spring and autumn nights, when the night outside temperatures are tolerable, fans can be more efficient than air conditioning for night-time sleeping comfort. In houses with ceiling fans, as in numbers six, nine and twelve, the operation of the AC system is limited to six months in the year, whereas in the other cases without ceiling fans, which are perceived as old-fashioned, it extends to nine months. Therefore, it is favourable to install fans in bedrooms and all living areas, which would significantly reduce the use of the cooling systems.

There is some evidence in this section that the efficiency of the cooling system may affect the amount of energy in the cooling load. It is thus essential to install an adequately efficient AC system in dwellings, related to the level of energy efficiency sought in individual high-performance homes. Bearing in mind that it is also necessary to combine different techniques of ventilation (stack, as used when dumping heat behind a suspended ceiling or cross-ventilation for cooling of occupants), the installation of fans is also recommended to reduce the operating period for the AC in certain months. The results of this study emphasise the importance of the installation of fans as a comfort tool in occupied rooms. The use of fans as an adaptive approach can create a comfortable environment when temperature and relative humidity levels are within the acceptable ranges and consequently would reduce cooling energy consumption in those rooms. Therefore, identifying the months and times of a day through the use of control systems to operate mechanical cooling within the warmest thermostat settings that still achieve comfort, while using fans for as long as possible at other times, could substantially reduce the cooling loads and energy bills.

7.2.6 *Energy efficient construction*

When considering the dwelling's envelope, it is important to consider the construction method as well as the materials used in the dwelling. Contemporary construction of residential buildings throughout Saudi Arabia can be classified typically as reinforced concrete systems. Various types of concrete products are employed in the construction of dwellings, including concrete blocks, floor tiles and precast concrete. Walls are mostly constructed with concrete brick of 20 to 25 cm thickness, with very high conductivity and insufficient thermal resistance. The wall structures need to be of a heavy material of large thermal capacity that provides long time-lag characteristics to keep interiors cool during the daytime. Insulating the mass externally, moreover, may help to achieve this, but is seldom done in the region. It appears that Dammam's dwellings have a variance of exterior wall thickness which, consequently, affects the resistance to heat transfer across walls and significantly affects the thermal performance of dwellings. Almost all well-performing homes were found to have an external wall thickness of 30cm including the insulations, whereas nearly all badly-performing homes have an external wall thickness of 25cm or less, including the insulation, if available. Furthermore, the thermal conductivities of the bricks and concrete blocks as construction materials used in the structure of the studied homes were very high. Therefore, better insulation in the dwellings' walls is clearly required.

Considering the fact that energy efficient dwellings should respond to the climate as well as site conditions, constructing in such an extreme climate should be thermally earth-coupled to the more stable ground temperatures, and yet still able to release the internal heat gained during hot days, typically by opening windows. However, most of the studied Dammam homes seemed to be constructed without benefiting from the available passive summer cooling, so they act as a hot bridge rather than a coolth store. It is evident that most of the studied homes clients/builders bear little consideration to the construction materials using concrete blocks, as the most popular material in the market, which do not adequately meet the basic requirements in such climate.

Insulating dwellings is critical in such a climate zone, to exclude the harshness of the climate and create comfortable homes. Roofs, floors and external walls should be insulated to minimise heat gain during the day and maximise heat loss at night. It is evident that well-insulated homes help to provide better indoor conditions and consequently user satisfaction. However, it appears in this research that dwellings aged fifteen years and older have no insulation, except those with high income owners who could build their dwelling to a higher standard. The data reported here appear to support the assumption that having no insulation in the dwelling could worsen the situation and increase the energy consumption, without getting to the point of a satisfactory internal temperature.

It is also worth noting that, when insulating walls surrounding an air conditioned space in a hot and humid climate, the insulation material could be damaged by being saturated by the condensation which also increases the risk for excess dust mite populations and the concentrations of mould spores. Placing the insulation under the internal plasterboard wall, for example, causes the dew-point to form condensation under the plasterboard. Dwelling number five, constructed 22 years ago, had suffered from this issue before and the affected areas had been renovated with condensation-resistant materials. Therefore, the choice of materials and finishes that are resistant to damage from condensation is essential. It is almost certain that walls with high thermal mass can store 'coolth' and have fewer dew-point problems than lightweight insulated walls. Moreover, reflective foil insulation is less affected by condensation and is highly suited to cooling climate applications, as it reflects unwanted heat out while not re-radiating it in.

7.3 Adaptive opportunities

The following section reviews a number of the adaptive enhancements that can be made to Dammam's homes to improve their thermal performance, including opening windows and dealing with infiltration, cooling and ventilation systems, landscaping and shades, and occupant behaviour or lifestyle.

7.3.1 *Opening windows and infiltration*

As ventilation and infiltration through windows affect heat transfer to and from a dwelling, heat transfer by mass transfer effects is caused by a difference between outdoor and indoor air temperatures. The density difference between air at outdoor and indoor air temperatures generates an upward flow of the lighter air. A heat flow is generated due to the airflow produced by ventilation and infiltration and is clearly exemplified by the cases undertaken in the cool season where dwellings are in the free-running mode, see for instance Figure 6.25.

In this study, it was found that occupants in all cases have operable windows and were able to open windows mainly in the cool season for air circulation during the day/night time over the periods between responses. Most of the use of opening windows/doors was in the afternoons, and almost all of the adaptations were during the period of relative humidity of less than 60%. So people might instinctively feel that if the outdoor air is saturated with moisture or not since they go out and walk into the dwelling. People therefore appear not to be fully dependent on air-conditioning systems, and to achieve adequate ventilation levels people were actively modifying their homes to allow or prevent natural ventilation by opening or closing windows. However, an interesting result is that all dwellers used the doors as a preferable way of adaptation in their homes instead of opening windows which is perhaps due to the preconception of the adversity of the outdoor conditions (i.e. high humidity, temperatures and dust storms) making the opening of internal doors always a more effective choice.

Another important practical improvement could be made by minimizing the number of windows by blocking the west-facing openings if applicable or any additional windows in rooms. It was established in this study that a window was placed in every possible wall inside the rooms in cases thirteen and fifteen, and it could be worth considering blocking and blinding all unnecessary extra openings in rooms, especially those extra windows in the west façade, to reduce the heat gain in these rooms. An example of blocking unnecessary windows is perhaps seen in dwelling number five, where the studied bedroom and living room used to have three windows, and then the owner blinded the middle opening in both rooms and filled them with blocks of cement permanently. During the informal interview, the owner of the house said *"that helped these rooms to keep the internal conditions more stable"*. Therefore, there is an opportunity for further work looking at how effective blinding of unnecessary windows would be to increase comfort and reduce cooling energy consumption for occupants. Another enhancement is to replace single-glazed windows with double- or treble- glazed windows, which evidence from this study shows might improve the energy performance of the dwelling significantly.

7.3.2 *Cooling and ventilation systems*

It is recommended in the first place to choose highly efficient equipment for cooling dwellings, or to upgrade the system when it reaches the end of its life span, refurbishing with a more efficient system. In house number thirteen, for example, the occupant stated in the questionnaire that it is expensive to maintain the cooling system and chose not to maintain the equipment regularly. However, by extrapolating the fact that he pays very high energy bill per square meter and the age of the house age is more than 25 years; it is obvious that the cooling system lifespan has been exceeded and needs to be replaced in the near future. When asked, the occupant said that "*we have had this AC system since we bought the house fifteen years ago and we haven't thought to replace it.*" However, in house number three, with the same dwelling age and income level and other design factors, they stated that the cooling system is not expensive to maintain, which accounts for its higher cooling system efficiency. These results support the idea that having an efficient AC system that is regularly maintained can reduce energy bills and improve internal comfort as well.

7.3.3 *Landscapes and shades*

The evidence presented in the earlier section suggests that it is important to consider the shading of the whole building to exclude solar access. It is important to lower the ground temperature, thus planting around the dwelling is fundamental. Moreover, it is important to spread the experience of good examples, as in dwelling number six, in order to build up knowledge towards optimum solutions. Furthermore, as suitable shading devices are recommended, shading the current western, southern and eastern fenestrations of dwellings is an ideal solution that could reduce the impact of the external insolation, as well as enhance the dwellings' appearance and indoors' conditions.

Although it was found that occupants rely on blinds and curtains to screen the windows, the type of curtains or blinds also affects the thermal comfort. It is important, thus, to think carefully about how the room is furnished and shaded internally. Each occupied room has materials that get warmer, for example, transparent or light curtains could aggravate the heat radiation inside the room. As in house number five, the use of heavy curtains for summer afternoons and winter nights might be an economical solution that can be implemented in bedrooms and consequently enhance the indoor conditions. Therefore, the choice of optimal furniture, as well as the type of window shades, affects the energy demand for cooling occupied rooms as well as the thermal comfort.

7.3.4 *Occupant lifestyle*

All above mentioned factors are mostly related to the dwelling's design and technologies, as opposed to behaviour. But since the dwelling is occupied by humans, failure of the human component can lead to failure in the performance of dwellings. This makes occupancy behaviour one of the weakest links in the dwelling's energy efficiency and performance. Recently, several studies have confirmed the impact of the users' behaviour on a building's energy consumption and conservation. Accordingly, it is not only important to get the design of the dwelling right, it is the lifestyle of the occupants that also matters. Therefore, along with a good design of a dwelling, the occupants' lifestyle should also correspond for an ideal high-performance dwelling.

In this study, the occupant's attitude and lifestyle have placed house number six as having the least energy consumed per square metre among the studied dwellings. Although house number six was constructed with an efficient cooling system, the attitude of the occupants was also clearly seen, in their being willing to accept being in a fairly warm temperature all the time, as well as operating the ceiling fans instead of AC during the acceptable indoor conditions throughout the year. Planting the surrounding area of the house and spending money on expensive plants to provide pleasant outdoor conditions, moreover, clearly indicate the role of the occupant's attitude in home lifestyle and performance.

What was surprising, however, was the measured mean ASHRAE scale and overall satisfaction reported in the lowest performing dwelling, number thirteen. With mean indoor temperature higher by 3K than the comfort temperature found in this study, massive energy consumption, and expensive operational cost, the occupants reported -0.1 in the ASHRAE scale and overall satisfaction with the indoor thermal conditions. As there is the possibility of bias in these responses, these data must be interpreted with caution, as many factors could lead to unsatisfactory conditions, as in all low performance homes in this study. The only possible explanation for this, nevertheless, might be related to the occupant's state of mind that they might have considered the internal temperature within a comfort condition and simply succumbed to the inevitable situation and adapted themselves to the existing circumstances.

On the other hand, the occupants of house number six, classified as being within the high-income household group in this study, will have an annual electricity bill with the new electricity tariff of just 2.5% of their annual income, and this could be less, with their conservation lifestyle. However, in house number thirteen, classified as being within the mid-income household group in this study, the residents will have to pay around 8% of their annual income for the new electricity tariff, which may be another expense for this family. It is likely, that this might then force them to take on loans, which might be the straw that broke the camel's back.

7.4 Summary

The main points that have emerged from the discussion in this chapter are:

1. In most cases a high performance envelope results in lower energy running costs.
2. A high performance dwelling envelope typically increases comfort levels in individual dwellings and well-being, and vice versa, although there are exceptions to this finding.
3. The performance of the dwelling is closely related to its location and, consequently, its orientation.
4. Good orientation has a strong positive impact on the dwelling’s indoor thermal condition and vice versa.
5. Buffering of living areas from the worst extremes of this often very hot climate has been shown to improve comfort levels experienced in the homes.
6. In some cases, the occupants’ comfort was compromised by the desire to provide impressive guest facilities in homes. Prioritisation of the need for, and value of, affordable comfort for occupants at the design stage is critical.
7. The smaller, the fewer and the better the orientation of windows, proved to be critical factors in the protection of homes against heat gain during the day and, in turn, the thermal experience of the dwellers as well as the dwellings energy consumption.
8. An example of shading of outdoor areas and walls of a home with trees shows a positive effect on the energy consumption in the adjacent home.
9. Installation of a more efficient AC system that was regularly maintained was shown to reduce the energy consumed in three homes.
10. The use of ceiling fans in three homes demonstrably reduced the operating periods for the AC during the autumn and spring months.
11. The highest performing homes had higher levels of roof and wall insulation.
12. Most of the homes were constructed with concrete blocks, so it was difficult to extrapolate from the collected data the impact of different building materials on the energy consumption in dwellings.
13. The results of this study suggest that an appropriate passive strategy for building design can be enough for desirable indoor conditions.

14. The energy consumption in the dwellings was not clearly linked to the comfort experienced in them.
15. Comprehension of what creates and enables comfort to be experienced in the studied dwellings is undeniably a complex phenomenon. While clear connections between the physical condition of the buildings and its services and the indoor thermal environment are evident, however, attitudes, social contexts and associated behaviours appear to be leading factors in the recorded occupied temperatures in these homes and, in turn, to the everyday comfort or discomfort experienced in them.

So this is what has been found through investigating seventeen of Dammam's homes during the summer season of 2013. The following chapter will draw up and form the main conclusions from the whole study and address the research questions and point the limitation and recommendations of the research as well as indicate ways to further work needed.

CHAPTER EIGHT: CONCLUSIONS

"People who jump to conclusions rarely alight on them."

Philip Guedalla

8.1 Introduction

Driven by the shortage of thermal comfort studies in the Gulf, this mixed method assessment study was dedicated to investigating the influence of physical design and occupants' behaviour on the thermal comfort experienced and the energy consumption of nineteen dwellings in the hot-humid Dammam region. The determination of the design guidance for the homes was addressed according to the thermal satisfaction of users in indoor spaces and the amount of energy consumed in the active cooling load in dwellings. Therefore, the main aim of this research was to find ways to achieve occupants' thermal comfort through improved building and system design and use, with the least energy consumption possible, in the Eastern region of Saudi Arabia. The research questions were established and presented in the introduction chapter, each contributing to guiding the researcher to meet the research objectives. This chapter accomplishes the work by showing the research findings as answers to the starting point of the research questions. Moreover, this chapter presents the conclusions achieved during the research process and illustrates the contribution to the body of knowledge. The limitations which challenged the researcher during the research process are also reviewed. In addition, the chapter will offer recommendations for the relevant authorities, guidelines for architects and advice to existing and future home owners. Finally, this chapter will also point to directions for future research in the field and further work to be carried out by the researcher.

8.2 Research conclusion

The first point to make is that the research has successfully met the main aims proposed for the study. The approach of this research was to investigate the design principles that enhance thermal comfort in domestic buildings with the least energy consumption possible, in the Eastern region of Saudi Arabia, taking into account the local extreme hot-humid climate conditions of Dammam city, together with the dwellings' physical characteristics and the occupants' comfort satisfaction and behaviour. Chapter Six detailed the different dwellings' features and their impact on the occupants' thermal experience. Furthermore, chapter Seven detailed the potential of the dwellings and the adaptive opportunities of the studied homes in order to enhance the thermal experience of the occupants and the energy conservations in Dammam homes. This contribution to the knowledge of the thermal and energy performance of the studied Dammam's dwellings could be appropriate for all Dammam's homes, and may also be applicable throughout the wider Gulf region as long as the same characteristics applied. The remainder of this section discusses the conclusions behind the completion of the research in reference to each of the research questions.

8.2.1 *Research question one:*

What is the indoor condition experienced and what level of thermal comfort are currently achieved in existing dwellings in Dammam?

This question was answered generally in chapter Five, and in detail in chapter Six, where each home was investigated separately. The occupied indoor air temperature variation recorded during the fieldwork ranged between just below 20°C to an outlier temperature of 39 °C during the hot season of August 2013. In the cool season of January 2014, however, the recorded occupied indoor air temperature ranged from a low of 18.2°C to a high of 29.5°C. The mean occupied temperature was 26.87°C in the hot season and 21.8°C for the cool season, with 5K difference between seasons, which makes an excellent opportunity for significant results in this study. As the mean outdoor and indoor air temperatures were 35.4°C and 27.4°C respectively, and a fifth of the occupied temperatures were found to be above 30°C, it is evident that people in Dammam do live in what people of many other regions of the world would consider as very hot conditions. The measurements taken also provide a valuable insight into the range of indoor relative humidity (RH) experienced in the studied homes, from 23% to 84% and from 56.2% to 96% for the hot season and cool season respectively. With the operation of the AC system, the mean RH of the whole sample, of 62% in both seasons, appears to be higher than the optimal standard of 55% that the HVAC standards aim for.

The first and significant point is that just over 70% of subject responses during both seasons in indoor conditions indicated one of the three central categories, slightly cool, neutral and slightly warm. Around the third of the responses reported being in a neutral condition during both seasons. As the difference in the average indoor air temperature in both seasons is fairly slight, the mean sensation reported in both seasons is slightly similar, that is, 0.02 and -0.03 for the hot and cool season respectively. The thermal sensation responses of all these dwellings have a significant, positive, weak correlation with the corresponding mean indoor temperatures, which indicates and supports the propositions that people are living in hot conditions and are adapting themselves to the mean indoor temperatures.

8.2.2 *Research question two:*

What is the range and norms energy consumption and the operational cost in Dammam's homes today?

Chapter Six presented the energy consumption patterns for eighteen existing and occupied dwellings in Dammam to answer this question, as details for only one dwelling were not accessible. The investigation included an exploration of energy consumption by consulting the official electricity bills to determine actual energy use during the year under investigation. The electricity bills, on one hand, showed a fairly coherent energy consumption across the utilised sample through the year with less energy consumption in the cool season. On the other hand, they indicated energy consumptions that varied according to building envelope and performance, as well as occupant behaviour, ranging between the lowest annual energy consumption of 14,907 kWh to as high as 118,656 kWh per annum. Moreover, due to the variation between dwellings, the electricity consumption according to kWh/m^2 per year, ranged between 89.3 kWh/m^2 up to 206.4 kWh/m^2, with an average of 123.33 kWh/m^2 per annum.

The operational cost of the studied homes was taken as the operational cost of the cooling system in each home, which included the cost of electricity bill and the cost of the AC system maintenance per annum. As 70% of the cost of the electricity bill was subject to the cooling demands, the amount of energy consumption depended on the number of cooling hours per day and the number of cooled rooms in the individual home, as well as the efficiency of the cooling system, besides all the other constraints that demand a greater cooling load, which in turn raises operational cost. In this study, the price of the annual electricity bill ranged between 970 SAR (£177) to 14,425 SAR (£2,622) per annum. Adding the cost of maintaining the cooling system, the operational cost ranged between 2,574 SAR (£468) to 19,825 SAR (£3,604), with an average cost of 7,706.7 SAR (£1,401) per annum. However, with the new electricity tariff that will possibly affect around half of the studied dwellings, almost all low performance dwellings, the annual operational cost could reach up to 28,480.9 SAR (£5,178.3), with an average of 10,193.6 SAR (£1,853.4) without the cost of replacement of any faulty parts during maintenance.

8.2.3 *Research question three:*

<u>What characteristics of the Dammam dwellings enhance the thermal experience and lead to lower operational costs?</u>

This question was answered in depth in chapter Seven by discussing the design opportunities in the nineteen Dammam dwellings. The key finding was that a high performance envelope results in lower energy running costs and typically increases comfort levels, and vice versa. The orientation of the dwelling, and especially its fenestrations, was found to have a strong impact on the dwelling's indoor thermal condition. More importantly, smaller and fewer fenestrations together with their better orientation, proved to be critical factors for the best thermal experience of the dwellers. Furthermore, the optimal use of buffer zones for living areas, has been shown to improve the comfort levels experienced in homes. The presence of insulation has also been shown to impact on the indoor condition and thus the comfort levels experienced. Installation of a more efficient AC system that is regularly maintained was shown to reduce the energy consumed in three homes. Finally, the use of ceiling fans along with a good design envelop has been clearly seen to enhance the thermal experience and reduce the annual energy consumption in homes.

8.2.4 *Research question four:*

<u>What adaptive opportunities are there for the individual homes/occupants' behaviour to be improved in order to enhance the thermal experience as well as reducing energy consumption?</u>

Chapter Seven investigated the adaptive opportunities of the nineteen dwellings and their occupants' behaviour, looking for ways of enhancing thermal comfort and reducing energy consumption. It was recognised that the high percentage of fenestration among the dwellings in this study may have contributed to the increase in the amount of energy consumption in those dwellings. Therefore, considering blocking or perhaps blinding all unnecessary extra openings in rooms permanently, especially those extra windows in the west façade, may boost the dwellings' performance. This study also supports the concept of having an efficient AC system that is regularly maintained, which may improve internal comfort and reduce the energy bills as well. Furthermore, it is fundamental to consider creating shading around dwellings by planting around the current western and eastern walls of dwellings, to reduce the impact of the external insolation. The use of heavy curtains in rooms, moreover, was in a single case an economical solution that can be implemented in rooms to enhance the indoor conditions.

In addition, people appear not to be fully dependent on air-conditioning systems, and actively adapt their internal environments to allow or prevent natural ventilation to achieve adequate ventilation levels. However, only rare occurrence of opening windows was detected in the dwellings and people in Dammam prefer the use of doors to semi-outdoor and uncooled spaces for climate and privacy reasons. Therefore, with the extreme outdoor conditions, the use of fans has played a vital role as much in providing a comfortable environment as in reducing the number of hours/months of operating the AC system throughout the year. Accordingly, equipping fans in all living areas has been found to significantly enhance the dwelling's thermal and energy performance.

On the other hand, the lifestyle and attitudes of the occupants, their social contexts and associated behaviours, appear to be key factors which affect the everyday comfort or discomfort experienced in these homes. Being willing to accept being in a fairly warm temperature during a hot day, operating the ceiling fans instead of AC during acceptable indoor conditions, and planting the surrounding area of the house to provide pleasant outdoor conditions all clearly indicate the role of the occupants' attitude in the home lifestyle and, in turn, the home's performance. Interestingly, with poor indoor conditions, the occupants' state of mind showed a great adaptation to the indoor conditions, considering the existing high temperature to be within their comfort zone, and the occupants simply succumbed to the inevitable situation within the home.

8.3 Contributions to knowledge

The research has made the following contributions to further knowledge in the area of domestic comfort research:

1. The identification of a wide scope of dimensions attributed to domestic comfort in Dammam area. The research has generated a more comprehensive description of thermal comfort and its relation with the energy consumed in dwellings, with an exploration of the physical design of the home and occupants' behaviour. These dimensions are collectively significant to occupants seeking to create a comfortable home environment.
2. It was found that for each home there were variations in lifestyle and attitudes, dwelling characteristics and social-cultural effects. Individuals in a particular

dwelling have their own strategies and apparatuses to achieve thermal comfort. Hence, it is not recommended to generalise the thermal comfort experience and standards of all people in different microclimates within a city and it is important to raise the level of knowledge of proper ways of achieving thermal comfort among the population in order to reduce residential energy consumption.

3. Generating a classification of domestic comfort in such an environment. This classification of domestic comfort has provided a complex representation of comfort, as discovered through this research. The facets acknowledged in this study are illustrative of a small sample of occupants of Dammam's homes, providing a set of characteristics acknowledged as key factors to home comfort.

8.4 Research limitations

The research was shaped by what was significant to the overall research aims; however, it was limited by what was possible for the researcher. As this research has examined existing residential envelopes in the Dammam region, there are some boundaries to the research results along with several limitations encountered by the researcher during the research process.

1. The topic was explored within the time constraints of a PhD study and the sample was constrained by time and resource limitations. Therefore, as the study involves the effect of the climate, and the surveys were done for only two seasons, it would be better to do a survey covering the whole year in order to get a richer picture.
2. The communication and cooperation with the volunteered occupants to get a sufficient amount of appropriate data was challenging, which might be attributable to the complex Saudi socio-cultural environment and barriers. For instance, it was difficult to obtain floor plans for all dwellings, due to the lack of assistance, as well as the availability of drawings, therefore, with only the support of some individual occupants the researcher had to take the measurements of the floor plans and draw them manually.
3. It was not possible to have the same samples in both seasons, as most of the participants felt it was a heavy duty to report their feelings of comfort twice daily as well as taking responsibility for the equipment in the hot season, although this had been explained in the first stage. Such constraints led to a smaller sample size for the cool season, which affected a full assessment of the causality of comfort and its relationship with high or low dwelling performance in the cool season.

4. The study is limited to the geographical coastal area of Dammam and the findings might not be applicable with inland cities within the eastern region. Therefore, with greater resources and more time, a larger sample size could have been used, which would have provided a better representation of households for the whole eastern region.

8.5 Research recommendations

The research offers a framework on which to base the design of comfortable homes in the Gulf hot-humid climates in general and in the Dammam context in particular. On the basis of the findings of this study, recommendations can be classified into four categories, for the different groups of people involved: decision makers, architects and consultants, clients and consumers, and finally, researchers in the field. The following general recommendations are made to suit both future and existing domestic buildings in Dammam, and to meet the requirement to achieve both thermal comfort and high energy performance.

8.5.1 *Recommendations for the decision makers*

1. The building codes in Saudi Arabia should be seriously revised to consider the impact of microclimates in domestic buildings, to ensure designing high-performance homes, mainly regarding the solar orientation of the building as well as the orientation and ratio of the fenestration within the façade.
2. Revise and update the approval conditions for new housing permits, adding energy consumption qualities to the design requirements.
3. Revise and upgrade the city planning regulations for new developments in Dammam considering the solar orientation of the lots instead of the Qiblah direction, as a way to reduce the residential energy consumption.
4. Raise public awareness regarding the level of energy consumption in the home, and educate the public about the importance of reducing energy consumption to benefit the individual household budgets.

8.5.2 *Recommendations for architects and consultants*

1. It is crucial to introduce, guide and encourage the clients commissioning the home at the stage of decision making to the appropriate choices in designing high-

performance dwellings to obtain thermal comfort and future economic satisfaction.

2. A north-south orientation should be considered in the location of all liveable rooms in the home schematic design, regardless of the direction of the street.
3. Make sure during the construction stages to include efficient, high resistance insulation in the whole building envelope, including roof, walls, floors and all openings, to prevent or decelerate the heat traversing from the outdoor environment.
4. For installing the insulation, it is recommended to hire qualified professionals to take account of VP reversal and risk of interstitial condensation.
5. Use an efficient insulated double or maybe a triple glazing to preclude any direct solar radiation entering the home.
6. The window-wall ratio should be reduced as much as possible, as a ratio of more than 20% showed an increment in the energy consumption of dwellings for cooling demand.
7. Design effective external shading devices and use landscaping to cool the surrounding environment and to assist in the reduction of energy consumption for air conditioning systems.
8. Living zones which are mostly occupied during the day should not be exposed to the western harshest thermal location of a home, so it is suggested to locate buffer spaces around living areas to limit the outdoors heat coming into these spaces.

8.5.3 *Recommendations for clients and consumers*

1. It is very strongly suggested to consult professionals at the stage of home choice decisions instead of choosing cheap products or relying on the construction contractor.
2. It is beneficial for existing low-performance dwellings to be retrofitted to meet the above guidance as much as possible, in order to enhance the indoor conditions as well as to reduce the electricity bill.
3. Using fans in the presence of acceptable thermal conditions has been shown to lead to a remarkable reduction in energy consumption, so it is suggested to reduce the annual energy bill by the use of fans between extreme seasons.
4. Setting the AC system thermostat at a higher temperature would help to reduce the cooling load on the dwelling and thus the lifespan of the cooling system.

5. It is advisable to attempt to change the daily lifestyle in favour of less cooling demand to reduce energy consumption.

8.5.4 *Recommendations for researchers in the field*

1. In the present study, the longitudinal survey represented only a small part of the work. It is important for assessing the impact of longitudinal surveys on the accuracy of the results that this kind of survey could be repeated on a larger scale in the eastern region.
2. As mentioned above, the data were only for hot and cool periods, so a study of the whole-year data would be desirable.
3. The potential of domestic solar panels for heating water during the winter period seems to be a large field of investigation to reduce energy use in residential buildings in Dammam.
4. It would be useful to study the homes of low income people and find out what is the thermal comfort experienced in those homes and what behaviours people attempt to enhance the thermal comfort.
5. Shading devices and solar characteristics of glazing in this region should also be investigated for different orientations, to reach an ideal window design for residential buildings in the local microclimate of Dammam.
6. The presence of adaptation for thermal comfort in homes has been limited in this study, so more research on adaptations over short periods of time and place in response to adaptive behaviour is recommended.
7. Looking at how effective blinding of unnecessary windows would be to increase comfort and reduce cooling demands.

8.6 Future work and research

Concerning the findings of this research and the current energy consumption situation in Saudi Arabia's residential sector, a need for a paradigm shift is essential to lead from the present situation to a low energy environment in the future. Hence, as the researcher is a lecturer at Dammam University in the eastern region of Saudi Arabia, the aim is to cooperate with the Dammam Municipality and Ministry of Housing, focusing on designing strategies for the housing sector to ensure and develop low energy design regulations in both authorities. Alongside these strategies, this aim requires the support of decision makers for a long-timescale plan to increase awareness of individuals as well.

On the other hand, the researcher has already established a specialised consultation centre for existing poorly-designed dwellings to improve the thermal comfort experienced in homes. It is hoped to spread the above recommendations to the existing architects' office, in order to cooperate with them for the post-construction services and refurbishments. In this sense, the hope is that the expansion of the study sample would create a large database for the Gulf researchers to explore in depth the issues of thermal comfort. Furthermore, future work could focus on researching and investigating new and creative architectural interventions that could improve a building's energy performance, taking into consideration local climates, weather patterns and architectural heritage. On the other hand, collaboration with different disciplines would also enhance and enrich the knowledge in such environments and cultures. A proposal has been already discussed with an academic colleague in education to find out what thermal environments are experienced in Dammam climate and what impact of a poorly-designed educational buildings have on the final educational products.

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APPENDICES

- Appendix I
  - The Original English version of the general questionnaire and the transverse survey
  - The interview questions
  - The Arabic translation version of the general questionnaire and the transverse survey
  - The Arabic translation version of the interview questions

- Appendix II
  - The interface of the ComfApp (The longitudinal survey)

- Appendixes III
  - A standard list of Garment/Clothing Insulation values (Source: reproduced from Al-ajmi et al., 2008)
  - A standard list of Metabolic Rates values for various activities, (Source: ISO 8996 2004, cited in Nicol et al., 2012)

- Appendix IV
  - The preliminary analysis of the summer field work

- Appendix V
  - An example of the data obtained from the longitudinal survey and the data loggers (case 18)

- Appendix VI
  - A copy of the proceeding paper participated in Windsor Conference 2014
  - A copy of the proceeding paper participated in Windsor Conference 2016

Appendix I

The Original English version of the general questionnaire and the transverse survey

Towards better buildings in composite climatic regions with reference to the Eastern Region of Saudi Arabia, approaches to user satisfaction in thermal comfort.

This field study/project is being conducted by Abdulrahman Mohammed Alshaikh, a Saudi Ph.D. research student in the School of Built Environment at Heriot Watt University, UK. This survey is about the quality of the indoor environment and any effects that it may have on thermal comfort of residents living in the eastern region of Saudi Arabia. Therefore, I would be very grateful if you could fill in this questionnaire to assist me in knowing how much, or how little, you like thermal environment level of your house.

Through previous work of this kind, it has been possible to recommend changes or guidelines for substantial improvement in such building environment. Consequently, the information you give the researcher will help him to become more aware of housing problems in the regions countries, which make further recommendations. So, the success of this study depends mainly upon your assistance. Any information you given will of course be treated in the strictest confidence.

Thank you in advance for your co-operation and support

Abdulrahman M. Alshaikh;
School of the Built Environment, Heriot-Watt University,
WA 3.36, William-Arrol Building, Edinburgh, EH14 4AS

THE HOUSE ADDRESS:
- *House Number*……………………………………
- *Street Name*…………………………………….
- *Street Intersection*……………………………….
- *Neighbourhood Name*…………..……………….
- *House Orientation*……………………………….

SECTION A: DEMOGRAPHIC INFORMATION

1. Gender: ☐ Male ☐ Female 2. Height: .... meters 3. Weight:.......... Kg
4. Age: ☐ below 20 ☐ 21-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ 61 or more
5. Are you in good health? ☐ Yes ☐ No, If No, please Explain:…………………………………………..….
6. What health problems do you have, aggravated by the temperature change?
   ☐ Respiratory problems *(ex. Asthma)* ☐ Skin problems *(ex. Eczema)* ☐ other……………………..………
7. What is your and your partner occupation? My occupation is …….……..……. My partner ………………..….
8. The family level of income (thousand SR): ☐ 1-5 ☐ 5-10 ☐ 10-20 ☐ 20-40 ☐ 40-more ☐ N/A
9. What is the size of your household? …...….Males ……….Females
10. How many adults/children in the house? ……….Adults ……….Teens (13-18) ……….Children (under 13)
11. Nationality: ……………………., *If NOT Saudi answer (a)*,
    a. How long have you been in Saudi Arabia (years)? ☐ 1-5 ☐ 5-10 ☐ 10-15 ☐ more……….
12. How long have you lived in this neighbourhood (years)? ☐ 1-5 ☐ 5-10 ☐ 10-15 ☐ more.………
13. How long have you lived in this building (years)? ☐ 1-5 ☐ 5-10 ☐ 10-15 ☐ more.………
14. Do you have a good relationships/interaction with you neighbours? ☐ Yes ☐ No
15. How safe is this neighbourhood (ex, for the children to play or family to walk…etc.)?
    Very Safe | 1 | 2 | 3 | 4 | 5 | Very Unsafe
16. How polluted is the air in this neighbourhood?
    Very Clean | 1 | 2 | 3 | 4 | 5 | Very polluted
17. Which crucial factors influenced you to choose to live here?
    ☐ Friends ☐ Relatives ☐ Neighbours ☐ Nearness to the workplace ☐ Financial reason
18. Do you find the overall environment is acceptable (i.e. noises, neighbours, aesthetics, sceneries, etc.)?
    ☐ Yes ☐ No, If No explain………………………………………………………………………………..

1

SECTION B:
THERMAL ENVIRONMENT AND PERSONAL INFLUENCES

Environmental quality and satisfaction of the condition of the building, to assess your overall liking of the building in which you live. Please rate your building on each of the following scales, and indicate like this (O), where (3) is the middle position:

Property size:...............X...............	**Overall, are you satisfied with**					**How important is**				
	Strongly dissatisfied	Dissatisfied	Neutral	Satisfied	Strongly satisfied	Very unimportant	Unimportant	Neutral	Important	Very important
1. … Outward appearance of your house?	1	2	3	4	5	1	2	3	4	5
2. … The interior designs of the house?	1	2	3	4	5	1	2	3	4	5
3. ... The thermal environment in the house?	1	2	3	4	5	1	2	3	4	5
4. … The back/front yard environment of the house?	1	2	3	4	5	1	2	3	4	5

5. Type of the building: ☐ Old house ☐ New villa ☐ Apartment ☐ Other: ………….
6. Building Age: ☐ 1- 5 years ☐ 5-10 years ☐ 10-15 years ☐ more than 15 years
7. Are you the owner or renter of this property? ☐ Owner ☐ Renter ☐ other.……….
8. How many hours/day do you spend in the house? ☐ 1-5 ☐ 5-10 ☐ 10-15 ☐ Almost all the day
9. What is the size of your house? ☐ 0-300 m^2 ☐ 300-800 m^2 ☐ 800-Upward m^2
10. How many floors are in this property? ☐ 1 ☐ 2 ☐ 3 ☐ more.……….
11. How many bedrooms are in this property? ☐ 1 ☐ 2 ☐ 3 ☐ more.……….
12. How many toilets are in this property? ☐ 1 ☐ 2 ☐ 3 ☐ more.……….
13. What type of mechanical ventilation do you have in your building?
    ☐ fans ☐ central HVAC ☐ Window air-condition ☐ air-condition units ☐ Other…………
    Where? ☐ Bedroom ☐ visiting room ☐ Sitting room ☐ Kitchen ☐ toilets ☐ everywhere
14. How often is the AC system of your house maintained over the year? ☐ 1 ☐ 2 ☐ 3 ☐ more.……
15. Is it expensive to maintain the AC system? ☐ Yes ☐ No
16. What part of your building do you like most:
    ☐ bedroom ☐ sitting room ☐ visiting room ☐ Other……………..Why?...
17. What part of your building do you dislike most:
    ☐ bedroom ☐ sitting room ☐ visiting room ☐ Other……………..Why?...
18. When do you decide to switch On the AC, day time and night, and in which month of the year?

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Day												
Night												

19. What is your maximum monthly energy bill during summer? ☐ 0-100 ☐ 100-200 ☐ 200-500 ☐ 500-Over

Any comments:…………………………………………………………………………………………………
………
………

2

SECTION D:
ENVIRONMENTAL CONDITION IN THE WHOLE BUILDING

Sitting room, Guest room and Bedroom (each zone separately)

In this zone the objective is to evaluate Environmental quality and of residents satisfaction of the condition of rooms within your modern building; to assess your overall liking of sitting room.
Please rate your where 3 is the middle position: room on each of the following scales, and indicate like this (O),

NOTE: From 1 To 15 Dealing With The SITTING ROOM Only.

Room size:...............x...............	Overall, are you satisfied with the ... in your Sitting room					How important is this in the Sitting room …				
	Strongly dissatisfied	Dissatisfied	Neutral	Satisfied	Strongly satisfied	Very unimportant	Unimportant	Neutral	Important	Very important
1. ….Noise level	1	2	3	4	5	1	2	3	4	5
2. ….Natural light (Sunlight)	1	2	3	4	5	1	2	3	4	5
3. .... Artificial light (electric light)	1	2	3	4	5	1	2	3	4	5
4. ….natural ventilation	1	2	3	4	5	1	2	3	4	5
5. ….artificial ventilation	1	2	3	4	5	1	2	3	4	5
6. .... amount of air movement	1	2	3	4	5	1	2	3	4	5
7. ….temperature	1	2	3	4	5	1	2	3	4	5
8. ….humidity level	1	2	3	4	5	1	2	3	4	5
9. .... shading level	1	2	3	4	5	1	2	3	4	5
10. ….windows open to outside	1	2	3	4	5	1	2	3	4	5
11. ….door opening to outside	1	2	3	4	5	1	2	3	4	5
12. ….the size (length x width) of the room	1	2	3	4	5	1	2	3	4	5
13. ….the height of the room	1	2	3	4	5	1	2	3	4	5

14. Please tick the box that best describes how often you are **too hot**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

15. Please tick the box that best describes how often you are **too cold**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

NOTE: From 16 To 30 Dealing With The GUEST ROOM (Majlis) Only.

Room size:...............x...............	Overall, are you satisfied with the ...in your guest room					How important is this in the guest room…				
	Strongly dissatisfied	Dissatisfied	Neutral	Satisfied	Strongly satisfied	Very unimportant	Unimportant	Neutral	Important	Very important
16. ….Noise level	1	2	3	4	5	1	2	3	4	5
17. ….Natural light (Sunlight)	1	2	3	4	5	1	2	3	4	5
18. .... Artificial light (electric light)	1	2	3	4	5	1	2	3	4	5
19. ….natural ventilation	1	2	3	4	5	1	2	3	4	5
20. ….artificial ventilation	1	2	3	4	5	1	2	3	4	5
21. .... amount of air movement	1	2	3	4	5	1	2	3	4	5
22. ….temperature	1	2	3	4	5	1	2	3	4	5

3

23. ….humidity level	1	2	3	4	5	1	2	3	4	5
24. .... shading level	1	2	3	4	5	1	2	3	4	5
25. ….windows open to outside	1	2	3	4	5	1	2	3	4	5
26. ….door opening to outside	1	2	3	4	5	1	2	3	4	5
27. ….the size (length x width) of the room	1	2	3	4	5	1	2	3	4	5
28. ….the height of the room	1	2	3	4	5	1	2	3	4	5

29. Please tick the box that best describes how often you are **too hot**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

30. Please tick the box that best describes how often you are **too cold**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

NOTE: From 31 To 45 Dealing With The **BEDROOM ROOM** Only.

Room size:…………….X……………

	Overall, are you satisfied with the ...in your bedroom					**How important is …… in the bedroom?**				
	Strongly dissatisfied	Dissatisfied	Neutral	Satisfied	Strongly satisfied	Very unimportant	Unimportant	Neutral	Important	Very important
31. ….Noise level	1	2	3	4	5	1	2	3	4	5
32. ….Natural light (Sunlight)	1	2	3	4	5	1	2	3	4	5
33. .... Artificial light (electric light)	1	2	3	4	5	1	2	3	4	5
34. ….natural ventilation	1	2	3	4	5	1	2	3	4	5
35. ….artificial ventilation	1	2	3	4	5	1	2	3	4	5
36. .... amount of air movement	1	2	3	4	5	1	2	3	4	5
37. ….temperature	1	2	3	4	5	1	2	3	4	5
38. ….humidity level	1	2	3	4	5	1	2	3	4	5
39. .... shading level	1	2	3	4	5	1	2	3	4	5
40. ….windows open to outside	1	2	3	4	5	1	2	3	4	5
41. ….door opening to outside	1	2	3	4	5	1	2	3	4	5
42. ….the size (length x width) of the room	1	2	3	4	5	1	2	3	4	5
43. ….the height of the room	1	2	3	4	5	1	2	3	4	5

44. Please tick the box that best describes how often you are **too hot**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

45. Please tick the box that best describes how often you are **too cold**:
☐ None ☐ 1-5 days ☐ 5-10 days ☐ 10-20 days ☐ 2-30 days ☐ always

Any comments:

………

………

………

………

………

………

4

SECTION E:
THE OCCUPANT'S THERMAL COMFORT

Please answer the following questions concerned with your thermal comfort, and rate your building in Summer on each of the following scale; Please rate your where (3) is the middle position: and indicate like this (X),

Please indicate the room which YOU occupy NOW ☐ **Time:** ☐

1. In this room which you occupy, please indicate on the scales below how YOU feel NOW.

Very Uncomfortable	1	☐	Very Dry	1	☐	Very Sticky	1	☐	Very Draughty	1	☐
Uncomfortable	2	☐	Dry	2	☐	Sticky	2	☐	Draughty	2	☐
Slightly Comfortable	3	☐	Slightly Dry	3	☐	Slightly Sticky	3	☐	Slightly Draughty	3	☐
Comfortable	4	☐	Not Dry	4	☐	Not Sticky	4	☐	Not Draughty	4	☐

2. Please indicate on the scales below how YOU feel NOW.

Hot	3	☐
Warm	2	☐
slightly warm	1	☐
neutral	0	☐
slightly cool	-1	☐
cool	-2	☐
cold	-3	☐

3. Please indicate on the scales below how YOU feel the air freshness NOW.

very stuffy	5	☐
stuffy	4	☐
neutral	3	☐
fresh	2	☐
very fresh	1	☐

4. Please indicate how YOU would like to be NOW. ☐ Warmer ☐ Cooler ☐ No Change
5. Do YOU feel either cool or warm NOW anywhere on your body? ☐ Yes ☐ No
   a. If yes, ☐ cool ☐ Warm
   b. Where?
   ☐ Head ☐ Shoulders ☐ Trunk ☐ Arms ☐ Hands ☐ Above knee ☐ Below Knee ☐ Feet
   c. Is it uncomfortable? ☐ Yes ☐ No
6. Have YOU noticed any movement of air? ☐ Yes ☐ No
   d. If yes, where? ☐ Face ☐ Neck ☐ Hands ☐ Feet
   e. Is it uncomfortable? ☐ Yes ☐ No
7. Are YOU NOW satisfied with your thermal environment? ☐ Yes ☐ No
8. With reference to the design of your building please indicate on the thermal scales below how YOU feel GENERALLY.

	Overall	Visiting room	Sitting room	Bedrooms	Kitchen	Toilets
Very Uncomfortable	1 ☐	1 ☐	1 ☐	1 ☐	1 ☐	1 ☐
Uncomfortable	2 ☐	2 ☐	2 ☐	2 ☐	2 ☐	2 ☐
Slightly Uncomfortable	3 ☐	3 ☐	3 ☐	3 ☐	3 ☐	3 ☐
Comfortable	4 ☐	4 ☐	4 ☐	4 ☐	4 ☐	4 ☐

9. Please indicate on the draught scales below how YOU feel GENERALLY.

	Overall	Visiting room	Sitting room	Bedrooms	Kitchen	Toilets
Very Draughty	1	1	1	1	1	1
Draughty	2	2	2	2	2	2
Slightly Draughty	3	3	3	3	3	3
Not Draughty	4	4	4	4	4	4
Please tick the suitable box/es if it is uncomfortable	☐	☐	☐	☐	☐	☐

10. Please indicate on the dryness scales below how YOU feel GENERALLY.

	Overall	Visiting room	Sitting room	Bedrooms	Kitchen	Toilets
Very Sticky	1	1	1	1	1	1
Sticky	2	2	2	2	2	2
Slightly Sticky	3	3	3	3	3	3
Not Sticky	4	4	4	4	4	4
Please tick the suitable box/es if it is uncomfortable	☐	☐	☐	☐	☐	☐

11. With reference to the design of your building please indicate on the scale below how YOU feel GENERALLY.

	Overall	Visiting room	Sitting room	Bedrooms	Kitchen	Toilets
Hot	3	3	3	3	3	3
Warm	2	2	2	2	2	2
slightly warm	1	1	1	1	1	1
neutral	0	0	0	0	0	0
slightly cool	-1	-1	-1	-1	-1	-1
cool	-2	-2	-2	-2	-2	-2
cold	-3	-3	-3	-3	-3	-3
Please tick the suitable box/es if it is uncomfortable	☐	☐	☐	☐	☐	☐

12. Please indicate on the scale below how YOU feel the air freshness GENERALLY

	Overall	Visiting room	Sitting room	Bedrooms	Kitchen	Toilets
very stuffy	5	5	5	5	5	5
stuffy	4	4	4	4	4	4
neutral	3	3	3	3	3	3
fresh	2	2	2	2	2	2
very fresh	1	1	1	1	1	1
Please tick the suitable box/es if it is uncomfortable	☐	☐	☐	☐	☐	☐

13. Are you GENERALLY satisfied with your thermal environment? ☐ Yes ☐ No

6

The interview questions

SECTION F: (INTERVIEW)
GENERAL FEELING AND PERSONAL EXPERIENCE

The following questions ask for your general feelings about the building and your personal experience,

1. Do you like to live in this building without any changes? ☐ Yes ☐ No
   Why? ………
   ………
2. Generally, between 2PM and 5PM in summer do you feel relaxed and take a nap? ☐ Yes ☐ No
   Where? And why?……………………………………………………………………………………………
   ………
3. Where do you sleep on summer nights?
   ☐ bedroom ☐ sitting room ☐ visiting room ☐ Other……………..
   If not in the bedroom, could you specify why?
   ………
   ………
4. Would you find this an acceptable environment to live in? ☐ Yes ☐ No
   Why? ………
   ………
5. Do you enjoy the outdoor space? ☐ Yes ☐ No
   Why? ………
   ………
6. Can you go outside your building at any time during summer? ☐ Yes ☐ No
   Why? ………
   ………
7. What could prevent you from enjoying outdoor space?
   ☐ Wind ☐ Noise ☐ Dust ☐ Temperature ☐ Humidity ☐ Other……………
8. Do you prefer to live in a newly built traditional design building with narrow shaded streets even if they are constructed using modem materials with passive ventilations' solutions? ☐ Yes ☐ No
   Why? ………
   ………
9. What aspects of the new design of building do you think are better for you in this climate region?
   ………
   ………
10. What problems at your house prevent reaching the thermal comfort wanted?
    ………
    ………
11. Do you enjoy passive cooling/heating? To what extent is your enjoyment? ☐ Yes ☐ No
    ………
    ………
12. To what extent are you willing to reduce your habit of AC dependency in favour of passive cooling and accept a lifestyle change?
    ………
    ………
13. What aspects of passive design can be implemented to the house for maintain building comfort throughout the year? What can you make in your current houses?
    ………
    ………

7

14. What are the factors that influence your choice to open a window, for example, not to open the AC?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
15. Do you have other attitudes or expectations to comfort when you are in a house rather than public buildings such as offices, shops or mosques? What do you expect in each place?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
16. What make you thermally satisfied, and what is your best delight moment?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
17. How do the culture and norms affect the opportunities for adaptation?
    What form of adaption are you allowed to adapt yourself inside the house to enhance your comfort?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
18. Does the national costume affect comfort? ☐ Yes ☐ No
    To what extent is clothing fixed? So do you wear less clothing in your house?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
19. Is the national energy consumption playing a part of your anxiety? ☐ Yes ☐ No
    To what extent are you concerned about your energy consumption?
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
20. Did the questionnaire make you more aware of your building environment? ☐ Yes ☐ No
    Please give any additional information or comments, which you think, are relevant to the assessment of your house thermal environment.
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………
    ……………………………………………………………………………………………………

RESEARCHER USE ONLY

Outside temperature		**Metabolic rate**:	
Air temperature:		**Clothing rate**:	
Air velocity:		**Indoor air quality**:	
Humidity:		**Noise levels**:	
Mean radiant temperature:		**Light levels**:	

Room features: Size, furniture layout, materials, opening, and mechanical features… etc.

8

The Arabic translation version of the general questionnaire and the transverse survey

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

جامعة الدمام
UNIVERSITY OF DAMMAM

HERIOT WATT UNIVERSITY

نحو تصميم مساكن إقتصادية مستدامة في المنطقة المناخية المركبة في الخليج

المنطقة الشرقية من المملكة العربية السعودية كحالة دراسية، منهج البحث عن رضى وراحة المستخدم الحرارية.

يجري هذه الدراسة الباحث / عبدالرحمن بن محمد الشيخ ، وهو جزئ من مشروع درجة الدكتوراه في كلية هندسة البناء في جامعة هيريوت وات في المملكة المتحدة. هذا المسح موجه للمساكن في المنطقة الشرقية لدراسة حالة الأماكن المغلقة والآثار التي قد تترتب على الراحة الحرارية للسكان الذين يعيشون في هذا المناخ المركب من المملكة العربية السعودية. لذلك سيكون من دواعي سروري إذا كان بإمكانك ملئ هذا الاستبيان لمساعدتي في معرفة مدى الراحة الحرارية في منزلك.

من خلال الأعمال السابقة في هذا المجال فإن من الممكن أن تتوصل البحوث إلى تغيير المبادئ التصميمية لتحسين بيئة البناء بشكل كبير. وبناء على ذلك، فإن المعلومات التي تعطيها الباحث ستساعد بشكل كبير ليكون أكثر وعيا وإلماماً لمشاكل الإسكان في المنطقة، مما ينبني عليها توصيات لتحسين الوضع الراهن. لذلك، فإن نجاح هذه الدراسة تعتمد أساسا على مساعدتكم وإهتمامكم . وبالطبع أي معلومة خاصة تعطى للباحث ستعامل بسرية تامة.

شكرا لكم مقدما على تعاونكم ودعمكم..

م. عبدالرحمن بن محمد الشيخ
School of the Built Environment, Heriot-Watt University,
WA36.3William-Arrol Building, Edinburgh, EH14 4AS

القسم الأول: معلومات أساسية

1 الجنس: ☐ ذكر ☐ أنثى   2 الطول: .... متر   3 الوزن: .... كجم

4 العمر: ☐ أقل من 20 ☐ 21 30 ☐ 31 40 ☐ 41 50 ☐ 51 60 ☐ أكثر من 61

5 هل أنت في صحة جيدة؟ ☐ نعم ☐ لا   إذا كانت الإجابة بـ (لا)، يرجى التفصيل: ....

6 ما هي المشاكل الصحية التي لديك والتي تتفاقم بسبب تغير درجة الحرارة؟

☐ مشاكل في الجهاز التنفسي (الربو مثلا) ☐ مشاكل جلدية (الأكزيما مثلا) ☐

أخرى..................................

7 ماهي وظيفتك و وظيفة زوجتك؟ وظيفتي .... وظيفة زوجتي

....

8 دخل العائلة الشهري(ألف ريال) ☐ 1 ٥ ☐ ٥ ١٠ ☐ ١٠ 20 ☐ 20 40 ☐ أكثر من 40

9 كم عدد البالغين/الأطفال في المنزل؟ .... بالغين .... المراهقين (18 13) .... الأطفال (دون سن 13)

10 الجنسية: ....

11 منذ متى وأنت تعيش في هذه المدينة(سنوات)؟ ☐ أقل من ٥ ☐ ٥ ١٠ ☐ ١٠ ١٥ ☐ أكثر من ١٥

12 منذ متى وأنت تعيش في هذا الحي (سنوات)؟ ☐ أقل من ٥ ☐ ٥ ١٠ ☐ ١٠ ١٥ ☐ أكثر من ١٥

13 منذ متى وأنت تعيش في هذا المسكن (سنوات)؟ ☐ أقل من ٥ ☐ ٥ ١٠ ☐ ١٠ ١٥ ☐ أكثر من ١٥

14 هل لديك علاقات جيدة مع جيرانك؟ ☐ نعم ☐ لا   إذا كانت الإجابة بـ (لا)، السبب: ....

15 ما مدى أمن هذا الحي (مثلا، للعب الأطفال أو لمشي الأسرة... الخ)؟

آمن جداً	١	٢	٣	٤	٥	غير آمن

16 ما مدى تلوث الهواء في هذا الحي؟

نقي جداً	١	٢	٣	٤	٥	ملوث جداً

17 ماهي العوامل المؤثرة عليك للعيش هنا؟ ☐ الأصدقاء ☐ الأقارب ☐ الجيران ☐ القرب من العمل ☐ أخرى............

في رأيك، هل تجد أن البيئة العامة للسكن هنامقبولة عموماً؟ (الإزعاج، المناخ/المجتمع، المنظر،... الخ) ☐ نعم ☐ لا

إذا كانت الإجابة بـ(لا)،

لماذا؟...

1

القسم الثاني: معلومات عن المسكن

جودة البيئة الحرارية ورضا المستخدم لحالة المبنى، لتقييم رضاك العام للمسكن الذي تعيش فيه، يرجى تقييم المبنى الخاص بك في الجدول التالي، ووضع دائرة (O) حول مايناسبك، حيث (٣) هو الموقف المحايد:

		مامدى أهمية .... في المسكن عموماً؟					مامدى رضاك عن .... في مسكنك الحالي؟				
		مهم جداً	مهم	محايد	غير مهم	غير مهم أبداً	راضي جداً	راضي	محايد	غير راضي	غير راضي أبداً
1	.........الشكل الخارجي للمسكن	٥	٤	٣	٢	١	٥	٤	٣	٢	١
2	.........التصميم الداخلي للمسكن	٥	٤	٣	٢	١	٥	٤	٣	٢	١
3	.........البيئة الحرارية في المسكن	٥	٤	٣	٢	١	٥	٤	٣	٢	١
4	.........بيئة الفناء الأمامي/الخلفي في المسكن (الحوش)	٥	٤	٣	٢	١	٥	٤	٣	٢	١

5 نوع المبنى: ☐ بيت شعبي ☐ فيلا ☐ شقة ☐ أخرى:......................

6 عمر المبنى: ☐ أقل من ٥ ☐ ٥ ١٠ ☐ ١٠ ١٥ ☐ أكثر من ١٥ سنة

7 هل أنت المالك أو المستأجر لهذا المسكن؟ ☐ المالك ☐ المستأجر ☐ أخرى..... ... ...

8 كم ساعة في اليوم تقضيها عادة في المسكن؟ ☐ أقل من ٥ ☐ ٥ ١٠ ☐ ١٠ ١٥ ☐ أغلب اليوم

9 ماهي مساحة المسكن؟ ☐ أقل من 300 م2 ☐ 300 800 م2 ☐ أكبر من 800 م2

10 كم عدد الطوابق في المسكن الخاص بك؟ ☐ ١ ☐ ٢ ☐ ٣ ☐ أكثر............ ... .

11 في أي دور من المبنى تسكن؟ ☐ ١ ☐ ٢ ☐ ٣ ☐ غير ذلك........... ... .

12 كم عدد غرف النوم في مسكنك ؟ ☐ ١ ☐ ٢ ☐ ٣ ☐ أكثر.................. ... .

13 كم عدد دورات المياه في مسكنك ؟ ☐ ١ ☐ ٢ ☐ ٣ ☐ أكثر.............. ... .

14 مانوع التبريد في مسكنك ؟ ☐ مراوح ☐ تكييف مركزي ☐ مكيفات شباك ☐ سبلت ☐ أخرى.......... ... ...

15 أين يتم توفير التكييف؟ ☐ غرف النوم ☐ المجالس ☐ الصالة ☐ المطبخ ☐ الممرات ☐ الحمامات ☐ كل المنزل

16 كم عدد مرات الصيانة الخاصة بالتكييف خلال السنة؟ ☐ ١ ٥ ☐ ٥ ١٠ ☐ أكثر من ١٠

17 ماهو سبب الصيانة غالباً؟ ☐ الغبار ☐ تعطل دائم ☐ تعبئة فريون ☐ أخرى....... ... .

18 هل هي مكلفة صيانة التكييف في مسكنك؟ ☐ نعم ☐ لا

19 هل يعجبك تصميم المسكن بشكل عام؟ ☐ نعم ☐ لا

20 أي جزئ من المنزل ترتاح فيه ويعجبك أكثر من غيره ؟ ☐ غرفة النوم ☐ الصالة ☐ المجلس ☐ أخرى........... ....

21 السبب؟..

22 أي جزئ من المنزل لاترتاح فيه ولايعجبك ؟ ☐ غرفة النوم ☐ الصالة ☐ المجلس ☐ أخرى................... ...

23 السبب؟..

24 متى تقوم بتشغيل المكيف / وحدات التبريد خلال العام ليلاً ونهاراً؟ يرجى الإشارة بـ (X)،

	يناير	فبراير	مارس	أبريل	مايو	يونيو	يوليو	أغسطس	سبتمبر	أكتوبر	نوفمبر	ديسمبر
نهاراً												
ليلاً												

25 ما هو الحد الأقصى لفاتورة الكهرباء في فصل الصيف(ريال)؟ ☐ 50 200 ☐ 201 500 ☐ 501 1000 ☐ أكثر من 1000

26 مقارنة بالدخل الشهري لديك، هل تظن أن فاتورة الكهرباء غالية؟ ☐ نعم ☐ لا

27 بالعموم، أسعار فواتير الطاقة الكهربائية:

معقولة جداً	١	٢	٣	٤	٥	مبالغ في قيمتها

28 هل تهتم لإجمالي الطاقة المستهلكة في المملكة؟ ☐ نعم ☐ لا

29 هل تعلم كيف سيؤثر ازدياد استهلاك الكهرباء على الصعيد الشخصي؟ ☐ نعم ☐ لا

30 كيف ذلك؟..

إضافة أي تعليقات حول المبنى الخاص بك:

....

....

القسم الثالث: الإرتياح الحراري والعام في المبنى

(غرفة الجلوس، المجلس ، غرفة نوم)

الهدف هو تقييم جودة البيئة السكنية للساكنين ومعرفة حالة الارتياح داخل الغرف؛ لتقييم رضاك العام لغرفة الجلوس، المجلس وغرفة نوم. يرجى تقييم المكان في الجدول التالي، ووضع دائرة (O) حول مايناسبك، حيث (٣) هو الموقف المحايد:

ملاحظة: الأسئلة من ١ إلى ١٣ تختص بغرفة الجلوس (الصالة) فقط

مساحة الغرفة

............x............

	مامدى أهمية .... في الصالة عموماً؟					مامدى رضاك عن .... في صالتك الحالية؟				
	مهم جداً	مهم	محايد	غير مهم	غير مهم أبداً	راضي جداً	راضي	محايد	غير راضي	غير راضي أبداً
١. .... مستوى الضوضاء	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٢. .... توفر الضوء الطبيعي (ضوء الشمس)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٣. .... توفر الضوء الاصطناعي (ضوء الكهرباء)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٤. .... التهوية أو التبريد الطبيعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٥. .... التهوية أو التبريد الاصطناعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٦. .... حركة الهواء	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٧. .... درجة الحرارة	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٨. .... مستوى الرطوبة	٥	٤	٣	٢	١	٥	٤	٣	٢	١
٩. .... مستوى الظل	٥	٤	٣	٢	١	٥	٤	٣	٢	١
١٠. .... فتح النوافذ إلى الخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
١١. .... فتح الباب للخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
١٢. .... مساحة الغرفة (طول x عرض)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
١٣. .... ارتفاع الغرفة	٥	٤	٣	٢	١	٥	٤	٣	٢	١

ملاحظة: الأسئلة من ١٤ إلى ٢٦ تختص بالمجلس فقط

مساحة الغرفة

............x............

	مامدى أهمية .... في المجلس عموماً؟					مامدى رضاك عن .... في مجلسك الحالي؟				
	مهم جداً	مهم	محايد	غير مهم	غير مهم أبداً	راضي جداً	راضي	محايد	غير راضي	غير راضي أبداً
14. .... مستوى الضوضاء	٥	٤	٣	٢	١	٥	٤	٣	٢	١
15. .... توفر الضوء الطبيعي (ضوء الشمس)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
16. .... توفر الضوء الاصطناعي (ضوء الكهرباء)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
17. .... التهوية أو التبريد الطبيعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
18. .... التهوية أو التبريد الاصطناعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
19. .... حركة الهواء	٥	٤	٣	٢	١	٥	٤	٣	٢	١
20. .... درجة الحرارة	٥	٤	٣	٢	١	٥	٤	٣	٢	١

21. .... مستوى الرطوبة	٥	٤	٣	٢	١	٥	٤	٣	٢	١
22 .... مستوى الظل	٥	٤	٣	٢	١	٥	٤	٣	٢	١
23. .... فتح النوافذ إلى الخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
24. .... فتح الباب للخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
25. .... مساحة الغرفة (طول x عرض)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
26. .... ارتفاع الغرفة	٥	٤	٣	٢	١	٥	٤	٣	٢	١

ملاحظة: الأسئلة من ٢٧ إلى ٣٩ تختص بغرفة النوم فقط

مساحة الغرفة ....x.............	مامدى أهمية .... في غرفة نوم عموماً؟					مامدى رضاك عن .... في غرفة نومك الحالية؟				
	مهم جداً	مهم	محايد	غير مهم	غير مهم أبداً	راضي جداً	راضي	محايد	غير راضي	غير راضي أبداً
27. .... مستوى الضوضاء	5	٤	٣	٢	١	٥	٤	٣	٢	١
28. .... توفر الضوء الطبيعي (ضوء الشمس)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
29. .... توفر الضوء الاصطناعي (ضوء الكهرباء)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
30. .... التهوية أو التبريد الطبيعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
31. .... التهوية أو التبريد الاصطناعي	٥	٤	٣	٢	١	٥	٤	٣	٢	١
32 .... حركة الهواء	٥	٤	٣	٢	١	٥	٤	٣	٢	١
33. .... درجة الحرارة	٥	٤	٣	٢	١	٥	٤	٣	٢	١
34. .... مستوى الرطوبة	٥	٤	٣	٢	١	٥	٤	٣	٢	١
35 .... مستوى الظل	٥	٤	٣	٢	١	٥	٤	٣	٢	١
36. .... فتح النوافذ إلى الخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
37. .... فتح الباب للخارج	٥	٤	٣	٢	١	٥	٤	٣	٢	١
38. .... مساحة الغرفة (طول x عرض)	٥	٤	٣	٢	١	٥	٤	٣	٢	١
39. .... ارتفاع الغرفة	٥	٤	٣	٢	١	٥	٤	٣	٢	١

٤٠. مع الإشارة إلى تصميم المبنى الخاص بك ، يرجى الإشارة في ميزان الحرارة أدناه شعورك بشكل عام.

	المنزل بالعموم	المجلس	الصالة	غرف النوم	المطبخ	دورات المياه
غير مريح أبداً	١	١	١	١	١	١
غير مريح	٢	٢	٢	٢	٢	٢
غير مريح قليلاً	٣	٣	٣	٣	٣	٣
مريح	٤	٤	٤	٤	٤	٤

٤١. يرجى الإشارة إلى الجدول الوارد أدناه كيف تشعر عموما. من ناحية التهوية.

	المنزل بالعموم	المجلس	الصالة	غرف النوم	المطبخ	دورات المياه
التهوية عالية	١	١	١	١	١	١
مهواة	٢	٢	٢	٢	٢	٢
التهوية ضعيفة	٣	٣	٣	٣	٣	٣
لايوجد تهوية	٤	٤	٤	٤	٤	٤

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٤٢. يرجى الإشارة في ميزان الجفاف أدناه شعورك بشكل عام.

	المنزل بالعموم	المجلس	الصالة	غرف النوم	المطبخ	دورات المياه
جفاف عالي	١	١	١	١	١	١
جفاف	٢	٢	٢	٢	٢	٢
جفاف قليل	٣	٣	٣	٣	٣	٣
لايوجد جفاف	٤	٤	٤	٤	٤	٤

٤٣. مع الإشارة إلى تصميم المبنى الخاص بك يرجى الإشارة على مقياس الحرارة وتمثيل شعورك بشكل عام.

	المنزل بالعموم	المجلس	الصالة	غرف النوم	المطبخ	دورات المياه
حرارة عالية	٣	٣	٣	٣	٣	٣
دفئ	٢	٢	٢	٢	٢	٢
دفئ خفيف	١	١	١	١	١	١
طبيعي	٠	٠	٠	٠	٠	٠
برودة خفيفة	-١	-١	-١	-١	-١	-١
برودة	-٢	-٢	-٢	-٢	-٢	-٢
برودة عالية	-٣	-٣	-٣	-٣	-٣	-٣

٤٤ . يرجى الإشارة إلى مدى شعورك بإنتعاش الهواء عموما

	المنزل بالعموم	المجلس	الصالة	غرف النوم	المطبخ	دورات المياه
مختنق جداً	١	١	١	١	١	١
مختنق	٢	٢	٢	٢	٢	٢
طبيعي	٣	٣	٣	٣	٣	٣
منتعش	٤	٤	٤	٤	٤	٤
منتعش جداً	٥	٥	٥	٥	٥	٥

٤٥. هل أنت راض بالبيئة الحرارية في مسكنك بشكل عام ؟ ☐نعم ☐لا

لماذا؟

....

....

إضافة أي تعليقات حول المبنى الخاص بك:

....

....

....

أرجو توفير:

☐مخطط وواجهات ومساقط المنزل ☐ فاتورة الكهرباء في الصيف والشتاء ☐ صورللمجلس والصالة وغرفة النوم (إن أمكن)

ل:زنملا ناونع

- يبلا مقر.......................... ت........................
- عراشلا مسا..
- عطاقت..
- يحلا مسا...
- .... ىنبملا هاجتا...............................

5

HERIOT WATT UNIVERSITY

جامعة الدمام UNIVERSITY OF DAMMAM

القسم الرابع: الراحة الحرارية الحالية

إجابة على الأسئلة التالية المعنية براحتك الحرارية، قم بتقيم منزلك في فصل الصيف على كل من المقاييس التالية
يرجى وضع إشارة (X) عند الإختيار المناسب لك.

يرجى تحديد الغرفة التي تتجلس فيها الآن		التاريخ :		الوقت :	

١. في هذه الغرفة التي تجلس فيها الآن، يرجى الإشارة في الميزان أدناه كيف تشعر الآن.

١ التهوية عالية	١ رطوبة عالية	١ جفاف عالي	١ غير مرتاح للغاية
٢ مهواة	٢ رطوبة	٢ جفاف	٢ غير مرتاح
٣ التهوية قليلة	٣ رطوبة خفيفة	٣ جفاف قليل	٣ غير مرتاح قليلاً
٤ لايوجد تهوية	٤ لايوجد رطوبة	٤ لايوجد جفاف	٤ مرتاح

الإشارة إلى مدى شعورك بانتعاش الهواء الآن.

٥	مختنق جداً
٤	مختنق
٣	محايد
٢	منتعش
١	منتعش جداً

6. يرجى الإشارة في ميزان أدناه كيف تشعر الآن.

٣	حرارة عالية
٢	دفئ
١	دفئ خفيف
٠	طبيعي
-١	برودة خفيفة
-٢	برودة
-٣	برودة عالية

5. يرجى

7. أرغب في أن أحصل الآن على: ☐ أكثربرودة ☐ القليل من البرودة ☐ لا أريد أي تغيير ☐ القليل من الدفئ ☐ أكثر دفئا

8. هل تشعر برودة أو دفئ في أي مكان في جسمك الآن؟ ☐ نعم ☐ لا

9. إذا كانت الإجابة بـ (نعم)، بماذا تحس ؟ ☐ برودة ☐ حرارة

10. أين؟ ☐ الرأس ☐ الكتفين ☐ الرقبة ☐ الذراعين ☐ اليدين ☐ فوق الركبة ☐ الساقين ☐ القدمين

11. هل تزعجك البرودة أو الحرارة هذه؟ ☐ نعم ☐ لا

12. هل تحس بأي حركة للهواء؟ ☐ نعم ☐ لا

13. إذا كانت الإجابة بـ(نعم)، أين؟ ☐ الوجه ☐ الرقبة ☐ اليد ☐ القدم

14. هل تزعجك حركة الهواء ؟ ☐ نعم ☐ لا

15. هل تناولت أي شيء خلال 15 دقيقة الماضية؟ ☐ شراب ساخن ☐ شراب بارد ☐ خفايف ☐ وجبة رئيسية ☐ لاشيء

16. الرجاء إختيار مايطابق لباسك الآن:

☐ ملابس داخلية	☐ سروال طويل	☐ ثوب نسائي	☐ عقال	☐ شماغ	☐ طاقية	☐ قميص خفيف وقصير
☐ قميص طويل	☐ غترة بيضاء	☐ بدلة رياضية	☐ حذاء	☐ نعال	☐ صندل	☐ بلوزة بأكمام طويلة
☐ جوارب طويلة	☐ جوارب قصيرة	☐ بنطال طويل	☐ ثوب	☐ دراعة	☐ فستان	☐ لباس خفيف بدون أكمام
☐ بنطلون قصير	☐ تنورة طويلة	☐ تنورة قصيرة	☐ حجاب	☐ عباية	☐ شيلة	☐ بلوزة بأكمام قصيرة

17. الحركة (خلال الربع ساعة الماضية كنت...) ☐ جالس ومسترخي ☐ جالس وأعمل عمل خفيف ☐ واقف (حركة قليلة) ☐ واقف (حركة كثيرة) ☐ أمشي داخل المنزل ☐ أمشي في الخارج ☐ أخرى.............................

18. التكيف (أختر ماهو قيد التشغيل الآن...)
☐ الباب مفتوح ☐ الشباك مفتوح ☐ الأضواء مفتوحة ☐ التكييف يعمل ☐ التدفئة تعمل ☐ المروحة تعمل ☐ الستائر مغلقة

19. إذا كنت تستخدم تدفئة حالياً فماهو نوعها:
☐ فحم أو حطب ☐ مدفئة زيت كهربائة ☐ مدفئة كهربائة ☐ تدفئة مركزة ☐ لايوجد تدفئة ☐ أخرى........................

20. هل أنت راض حالياً عن البيئة الخاصة بك حرارياً ؟ ☐ نعم ☐ لا إذا كانت الإجابة بـ(لا) لماذا؟.......................
....

شكراً جزيلاً على إتاحة الفرصة، وإعطائي من وقتك الثمين...

The Arabic translation version of the interview questions

HERIOT WATT UNIVERSITY

بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

جامعة الدمام
UNIVERSITY OF DAMMAM

نحو تصميم مساكن إقتصادية مستدامة في المنطقة المناخية المركبة في الخليج

المنطقة الشرقية من المملكة العربية السعودية كحالة دراسية، منهج البحث عن رضى وراحة المستخدم الحرارية.

القسم الخامس: الشعور العام والخبرة الشخصية (مقابلة)

---

١. هل تحب أن تعيش في هذا المسكن دون أي تغيير؟ ☐نعم ☐لا

لماذا؟..

....

....

2. عموما، بين الساعة ٢ مساء و ٥ مساء في فصل ☐ الصيف أو☐الشتاء هل تشعر بالإسترخاء وتأخذ غفوة؟ ☐نعم ☐لا

إذا كانت الإجابة بـ(نعم) أين تنام؟ ☐غرفة النوم ☐ الصالة ☐ المجلس ☐ في العمل ☐ أخرى................

إذا لم يكن في غرفة النوم, هل بإمكانك أن تخبرني لماذا؟

....

....

....

3. هل تستمتع بالجلوس في فناء المنزل خلال هذا الفصل؟ ☐نعم ☐لا

لماذا؟..

....

....

4. ماهي النشاطات التي تقوم بها في فناء المنزل خلال فترة الشتاء؟ ☐نعم ☐لا

متى؟

ولماذا؟..

....

....

5. ماهي الأسباب التي قد تمنعك من الجلوس في فناء المنزل خلال هذا الفصل؟

☐الرياح ☐ الإزعاج ☐ الغبار ☐ درجة الحرارة ☐ معدل الرطوبة ☐أخرى......................

6. ماهي العناصر التي تتمنى إضافتها في فناء المنزل لكي تصل لغاية الراحة والإستمتاع خلال هذا الفصل؟

....

....

....

7. ماهي الأسباب الموجودة في مسكنك والتي تحول بينك وبين الراحة الحرارية المطلوبة؟

....

....

....

8. هل تستمتع بتقنيات التبريدأو التدفئة بدون إستخدام المكيفات كوسيلة أساسية (مثل المراوح)؟وإلى أي مدى هو إستمتاعك؟

....

....

....

9. هل تعلم كيف سيؤثر ازدياد استهلاك الكهرباء على الصعيد الشـ 1 ؟ ☐نعم ☐ لا

كيف ذلك؟..

....

....

10. ماهي العوامل التي تؤثر على قرارك لإختيار (فتح أو إغلاق النافذة أو المروحة) بدلاً من (فتح المكيف أو التدفئة) ؟

....

....

11. هل لديك توقعات مختلفة للراحة الحرارية في الأماكن العامة مثل المسجد، الأسواق، العمل...الخ مختلفة عن الراحة الحرارية في المنزل؟ ماذا تتوقع البرودة أو الحرارة في كل منها ولماذا؟

....

المسجد، ....الأسواق،

العمل...

12. مالذي يجعلك راضٍ عن بيئتك الحرارية؟ ماهو تصورك للحظة الجميلة والأكثر ارتياحا حراريا؟

....

....

13. إلى أي مدى تظن أن الأعراف والتقاليد تؤثرعلى فرص التكيف الحراري المناسب لكل شخص؟ ماهو شكل التكيف الأدنى والأقصى الذي تسمحه لنفسك داخل مسكنك لتصل لراحتك الحرارية؟

....

....

.14. هل تظن أن اللباس التقليدي يؤثر على الإرتياح الحراري ؟ وإلى أي مدى تتكيف بلباس أقل للحصول على الراحة في مسكنك؟

....

....

15. لو كنت صانع قرار، ماذا يمكنك أن تعمل لتخفيض إستهلاك الطاقة في المنازل ، بالإضافة لتحسين الراحة الحرارية؟

....

....

....

١٩. هل الاستبيان هذا جعلك أكثر وعياً بالبيئة والمبنى الخاص بك؟ ☐نعم ☐ لا

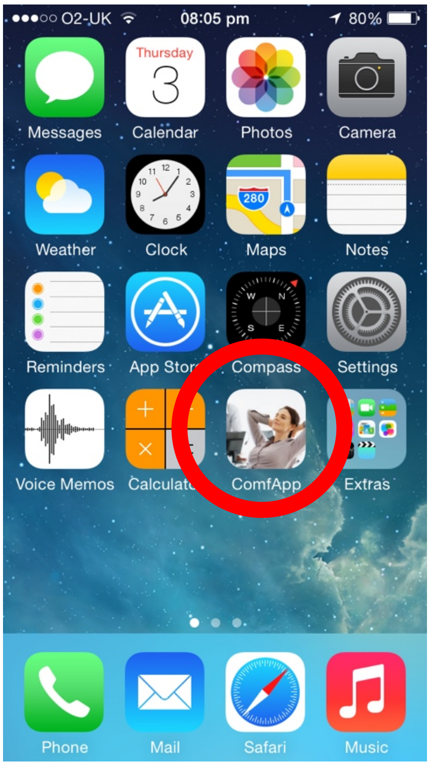
يرجى إعطاء أي معلومات إضافية أو تعليقات التي تظن أنها ذات صلة لتقييم البيئة الحرارية الخاصة بك.

....

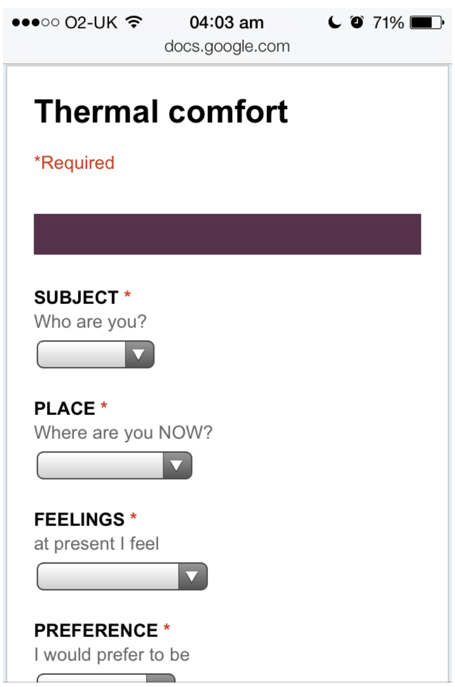
....

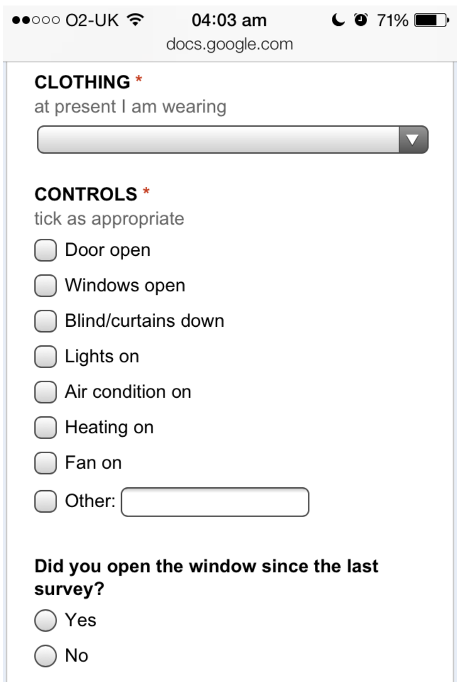
....

The interface of the ComfApp (The longitudinal survey)



-The ComfApp icon *-The final Arabic application interface*

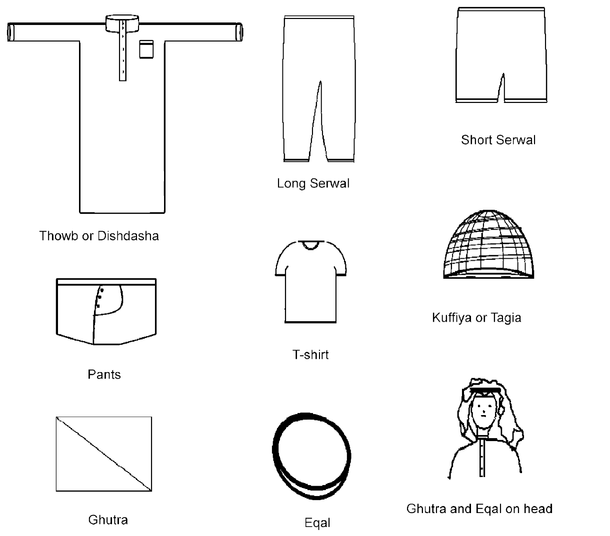




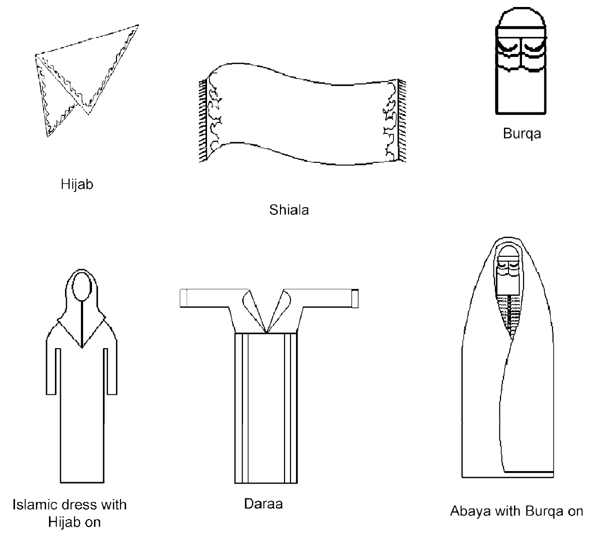
-The original application interface

Appendix III

A standard list of Clothing Insulation values (Source: reproduced from Al-ajmi et al., 2008)



Sample of Arabian Gulf traditional male clothing



Sample of Arabian Gulf traditional female clothing

- *<u>Characteristics of various Arabian Gulf male clothing materials used in the clothing shown in the figure above</u>*

Ensemble type	Code	Type/construction	Body surface area covered (%)	Fibre/content	Ensemble weight (kg)
Summer clothing	1	Underwear-pants	12	100% cotton	0.108
	2	Underwear-shirt with 1/3 sleeves	40	100% cotton	0.121
	3	Short trouser (short Serwal)	25	Polyester, cotton	0.125
	4	Long trouser (long Serwal)	44	Polyester, cotton	0.181
	5	Summer Thowb	81	Cotton, wool, polyester	0.419
	6	Kuffiya (or Taqia)	3	Cotton, polyester, nylon	0.017
	7	While Ghutra	10	Cotton, silk, polyester	0.130
	8	Sandal(s) or slippers	4	Leather	–
Winter clothing	9	Thowb or dishdasha	81	Wool	0.594
	10	Long sleeve cotton trouser	44	Cotton	0.181
	11	Kuffiya (or Taqia)	4	Cotton	0.017
	12	White/Red Ghutra or Shemagh	10	Wool, polyester	0.194
	13	Eqal	2	Wool	0.117
	14	Coat or thermo-coat (or Jacket)	64	52% Polyester, 29% viscose, 19% cotton	0.904
	15	Socks	14	Cotton, polyester	–
	16	Shoes	7	Leather	–

- *Characteristics of various Arabian Gulf female clothing materials used in the clothing shown in the figure above*

Ensemble type	**Code**	**Clothing ensembles**	**Body surface area covered (%)**	**Fibre/content**	**Weight (kg)**
'Traditional' clothing in'winter'	17	Winter Daraa	81	Velvet, wool	0.578
	18	Abaya	86	Polyester	0.665
	19	Long trousers	51	Polypropylene	0.215
	20	Shiala	12	Polyester	0.071
	21	Burqa	7	Polyester	0.022
	22	Bra	5	Nylon	0.049
	23	Pants	15	Cotton	0.028
	15	Socks	20	Cotton, polyester	0.054
	16	Shoes	9	Leather	–
'Traditional' clothing in 'summer'	24	Summer Daraa	81	Polyester–cotton	0.213
	20	Shiala	12	Polyester	0.071
	21	Burqa	7	Polyester	0.022
	25	Abaya	86	Polyester	0.665
	22	Bra	5	Nylon	0.049
	23	Pants	15	Cotton	0.028
	8	Sandals	4	Leather	–
'Islamic' clothing in'winter'	17	Winter Daraa	81	Cotton, polyester	0.713
	19	Long trousers	51	Polypropylene, cotton	0.215
	23	Pants	15	Cotton	0.028
	22	Bra	5	Nylon	0.049
	26	Hijab	12	Polyester	0.062
	15	Socks	20	Cotton, polyester	0.054
	16	Shoes	9	Leather	–
'Islamic' clothing in 'summer'	24	Summer Daraa	81	Cotton	0.213
	26	Hijab	12	Polyester	0.062
	23	Pants	15	Cotton	0.028
	22	Bra	5	Nylon	0.049
	8	Sandals	4	Leather	–

- *Thermal insulation values of Gulf male clothing ensembles in units of (clo) and m^2 1C W^{-1} unit*

Ensemble type/code	**Ensemble no.**	**Clothing ensembles**	f_{cl}	I_a		I_{cl}		I_T	
				clo	m^2 1C W^{-1}	clo	m^2 1C W^{-1}	clo	m^2 1C W^{-1}
Male summer clothing	1	Underwear-shirt with 1/3 sleeves, Short sleeve trouser, Thowb, Sandals	1.30	0.594	0.092	0.59	0.092	1.05	0.163
	2	Underwear-shirt with 1/3 sleeves, Short trouser, Thowb, Kuffiya, White Ghutra, Eqal, Sandals	1.35	0.594	0.092	0.69	0.107	1.13	0.175
	3	Underwear-shirt with 1/3 sleeves, Short trouser, Long trouser, Thowb, Kuffiya, White Ghutra, Eqal, Sandals	1.36	0.594	0.092	0.79	0.123	1.23	0.191
Male winter clothing	4	Underwear-shirt with 1/3 sleeves, Short trouser, Long cotton trouser, Thowb, Kuffiya, Ghutra/Shemagh, Egal, Shoes	1.46	0.594	0.092	0.84	0.131	1.25	0.194

	5	Underwear-shirt with 1/3 sleeves, Short trouser, Long cotton trouser, Thowb, Ghutra Shemagh, Egal, Jacket, Shoes	1.45	0.594	0.092	1.29	0.200	1.70	0.264

- *Total thermal insulation of Gulf female clothing in (clo) unit and m^2 1C W^{-1} unit*

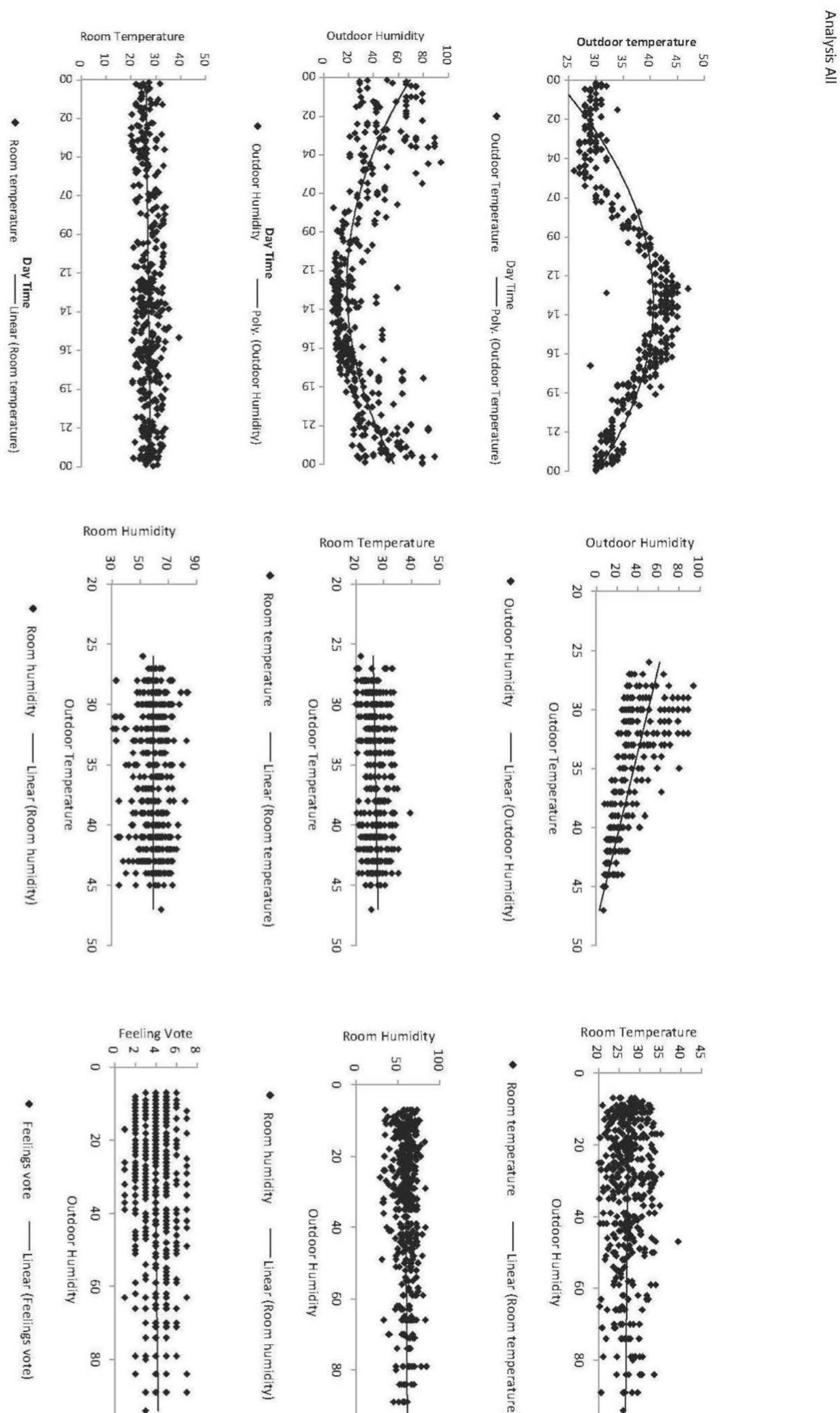
Ensemble type	Ensembles code	Clothing ensembles	f_{cl}	I_a		I_{cl}		I_T	
				clo	m^2 1C W^{-1}	clo	m^2 1C W^{-1}	clo	m^2 1C W^{-1}
'Islamic' clothing in summer	6	Summer Daraa, Shiala, Bra, Pants, Sandals	1.48	0.60	0.092	0.80	0.123	1.20	0.186
	7	Summer Daraa, Hijab, Bra, Pants, Sandals	1.48	0.60	0.092	0.80	0.123	1.20	0.186
'Islamic' clothing in winter	8	Winter Daraa, Hijab, Bra, Pants, Socks, Shoes	1.44	0.60	0.092	1.15	0.178	1.56	0.242
	9	Winter Daraa, Shiala, Bra, Pants,Socks, Shoes	1.43	0.60	0.092	1.17	0.181	1.58	0.245
	10	Winter Daraa, Shiala, Long trouser, Bra, Pants, Socks, Shoes	1.44	0.60	0.092	1.34	0.208	1.75	0.272
Winter clothing without Shiala	11	Winter Daraa, Long trousers, Bra, Pants, Socks, Shoes	1.39	0.60	0.092	1.17	0.186	1.59	0.247
Summer clothing without Hijab	12	Summer Daraa, Bra, Pants, Sandals	1.41	0.60	0.092	0.77	0.119	1.19	0.185
'Traditional' clothing in summer	13	Summer Daraa, Abaya, Shiala, Burqa, Bra, Pants, Sandals	1.79	0.60	0.092	1.38	0.213	1.71	0.265
'Traditional' clothing in winter	14	Winter Daraa, Shiala, Burqa, Bra, Pants, Socks, Shoes	1.55	0.60	0.092	1.01	0.156	1.39	0.216
	15	Winter Daraa, Abaya, Shiala, Burqa, Long trouser, Bra, Pants, Socks, Shoes	1.94	0.60	0.092	1.80	0.279	2.11	0.327
'Traditional' clothing in summer (without Shiala and Burqa)	16	Winter Daraa, Abaya, Bra, Pants, Sandals	1.51	0.60	0.092	0.85	0.131	1.24	0.192

A standard list of metabolic rates values for various activities, (Source: ISO 8996 2004, cited in Nicol et al., 2012:105)

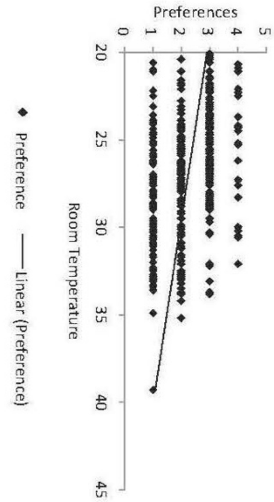
Class rate	Average metabolic (with range in brackets)		Examples
	W. m^{-2}	W	
0 Resting	65 (55 to 70)	115 (100 to 125)	Resting, sitting at ease
1 Low metabolic rate	100 (70 to 130)	180 (125 to 2325)	Light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal. Standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 2,5 kmh–1).
2 Moderate metabolic rate	165 (200 to 260)	295 (235 to 360)	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off- road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling lightweight carts or wheelbarrows, walking at a speed of 2,5 kmh–1 to 5,5 kmh–1, forging.
3 High metabolic rate	230 (200 to 260)	415 (360 to 465)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5,5 kmh–1 to 7 kmh–1. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	290 (>260)	520 (>465)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed great than 7 kmh–1.

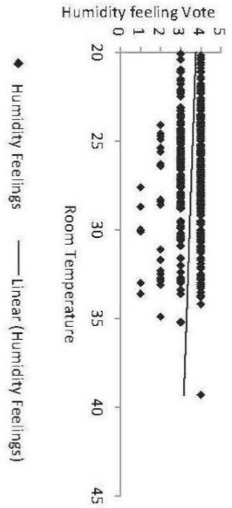
Appendix IV

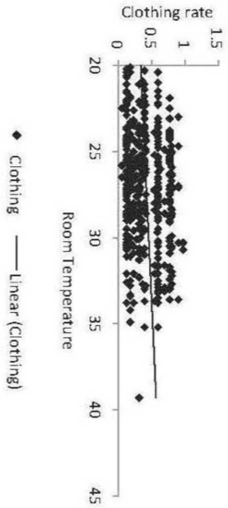
The preliminary analysis of the summer field work

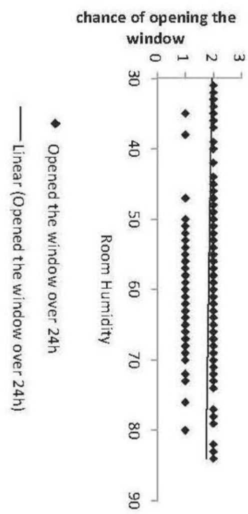


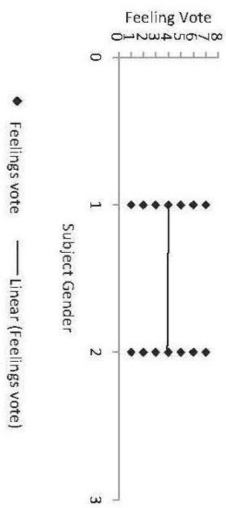
Analysis All

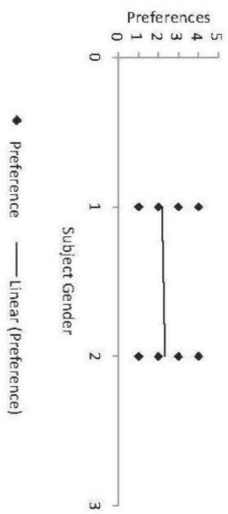


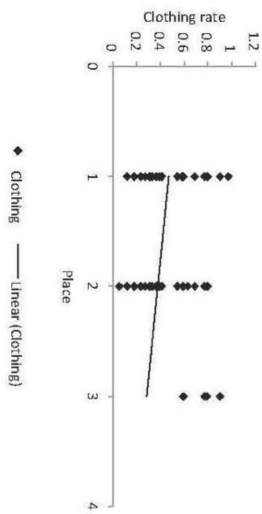


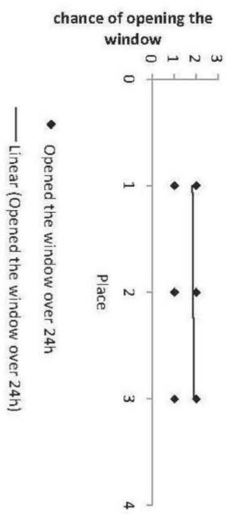


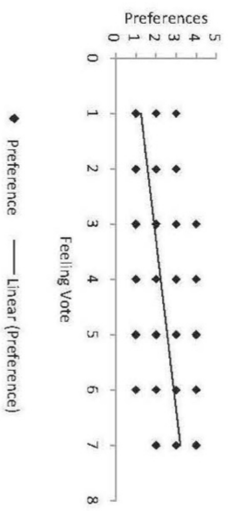




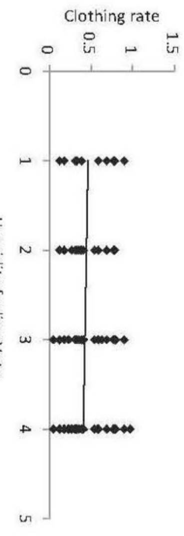


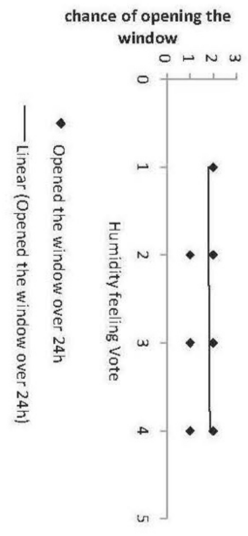


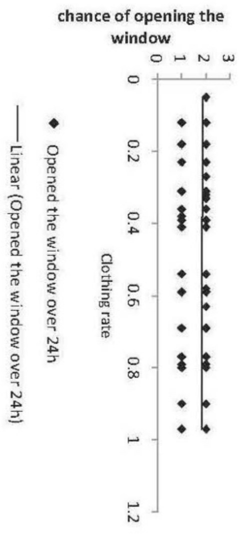




Analysis All







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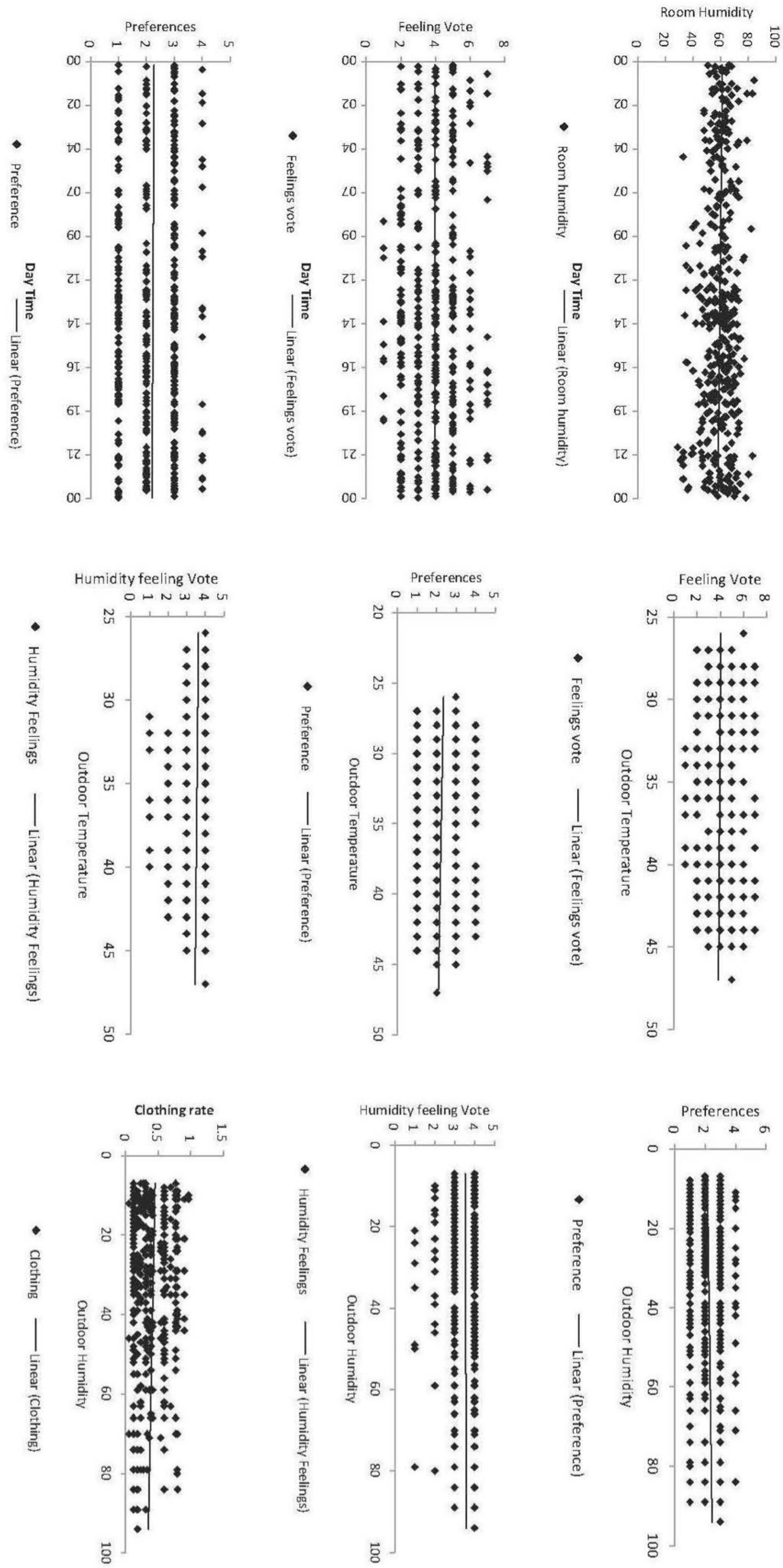

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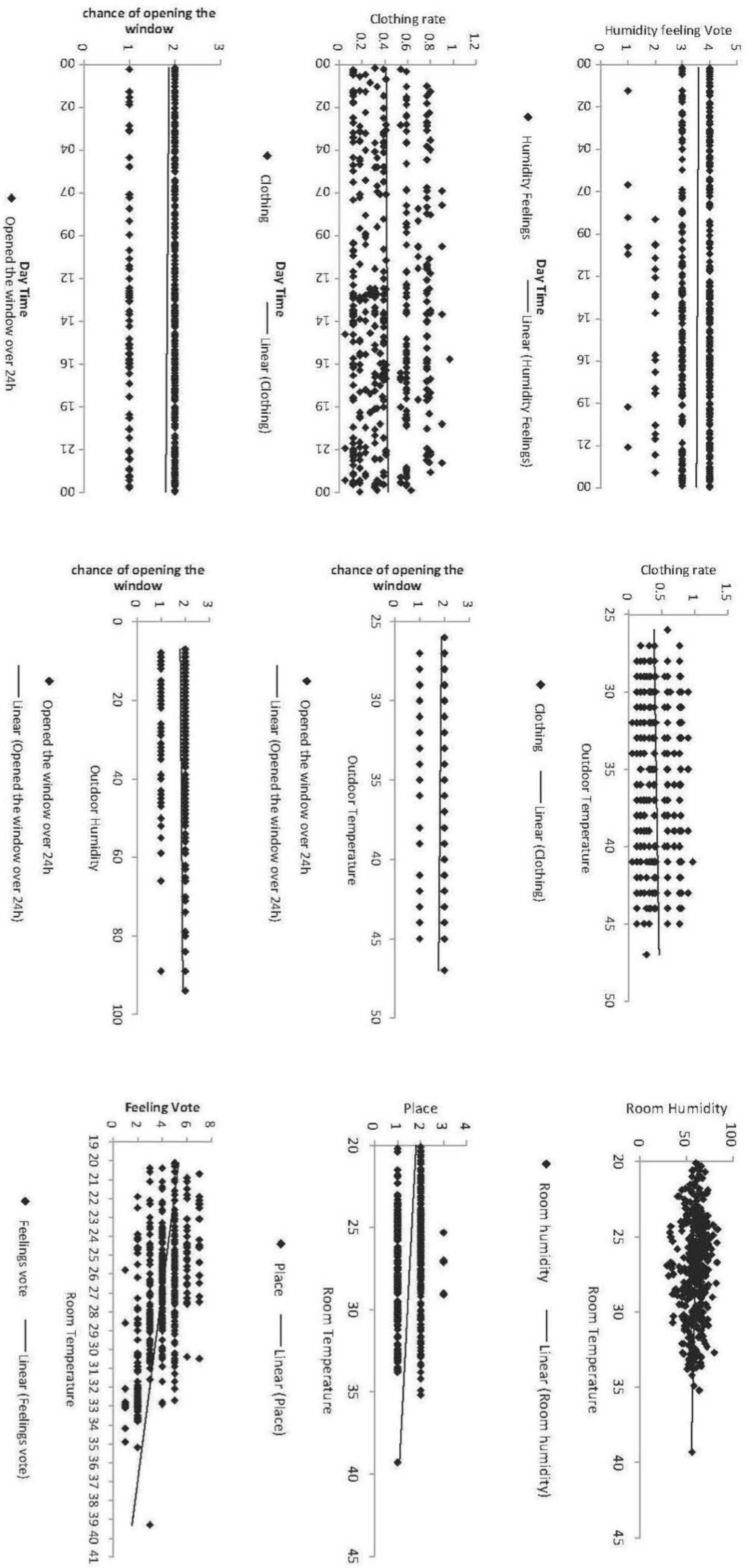

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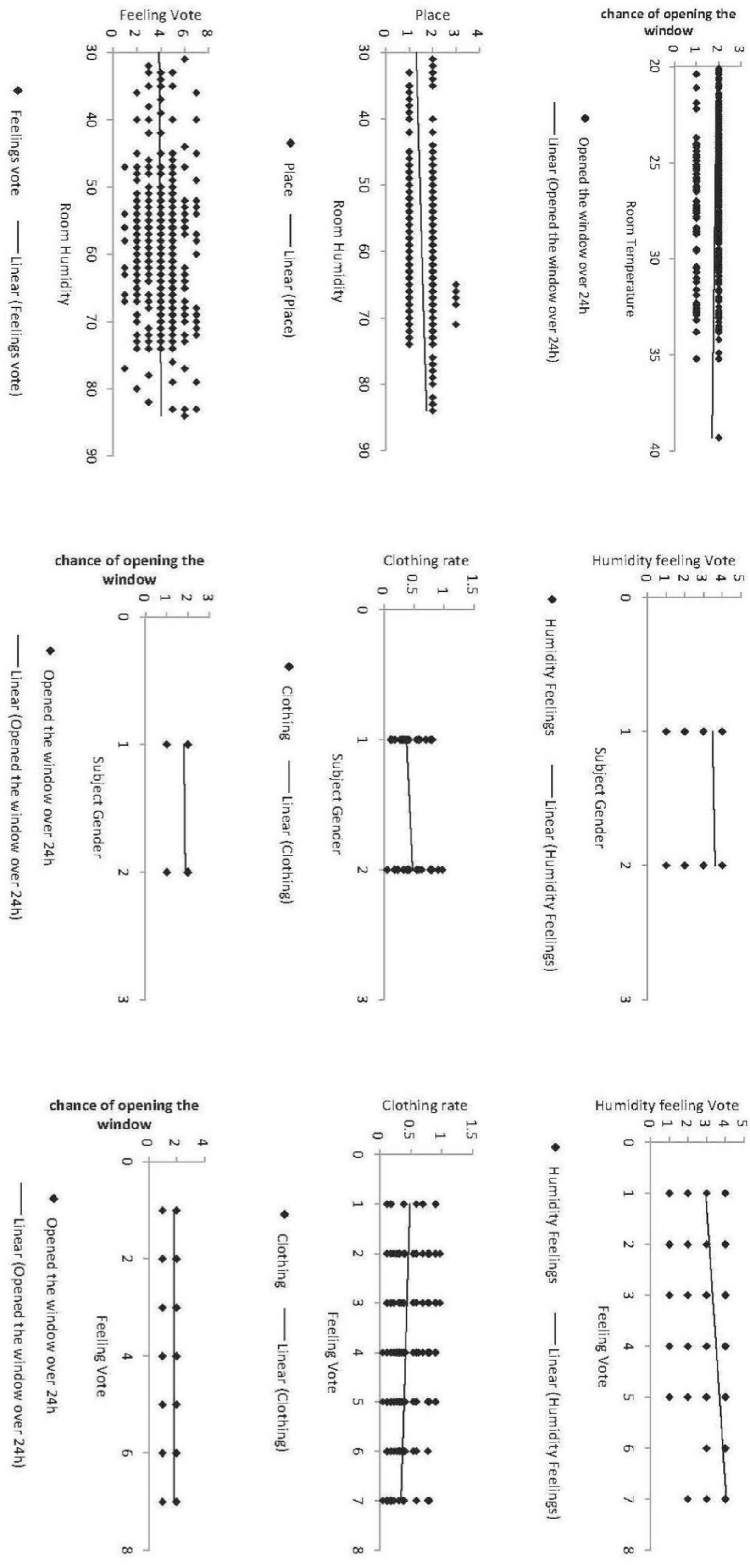

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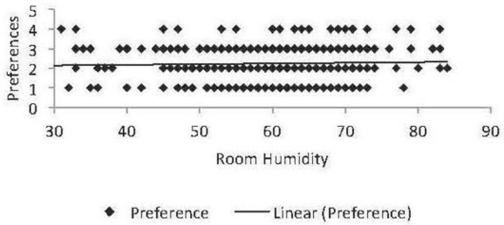
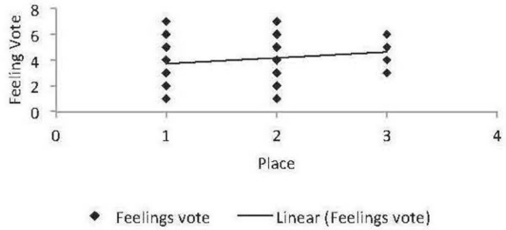
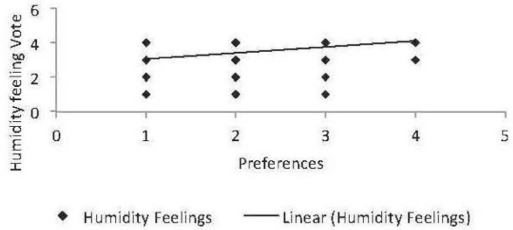
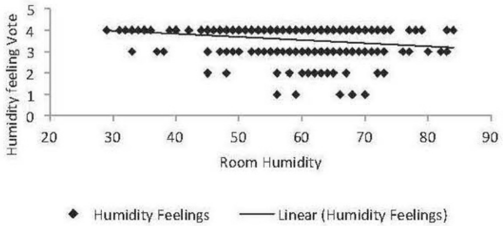
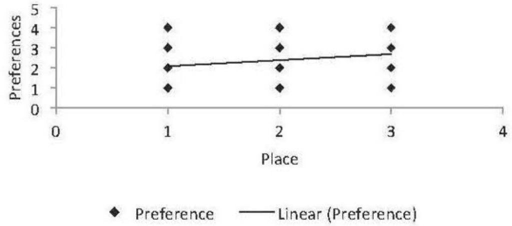
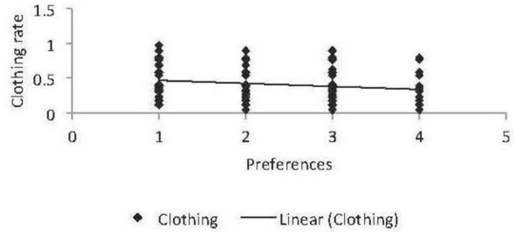


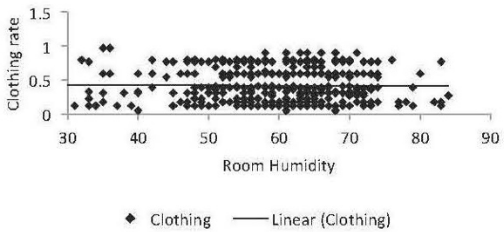


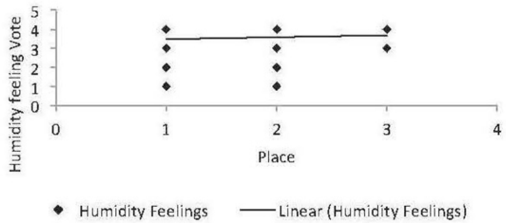


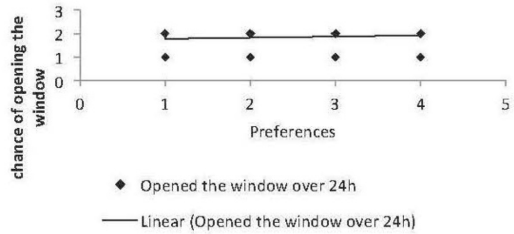












Appendix V

An example of the data obtained from the longitudinal survey and the data loggers (case 18)

Page 1

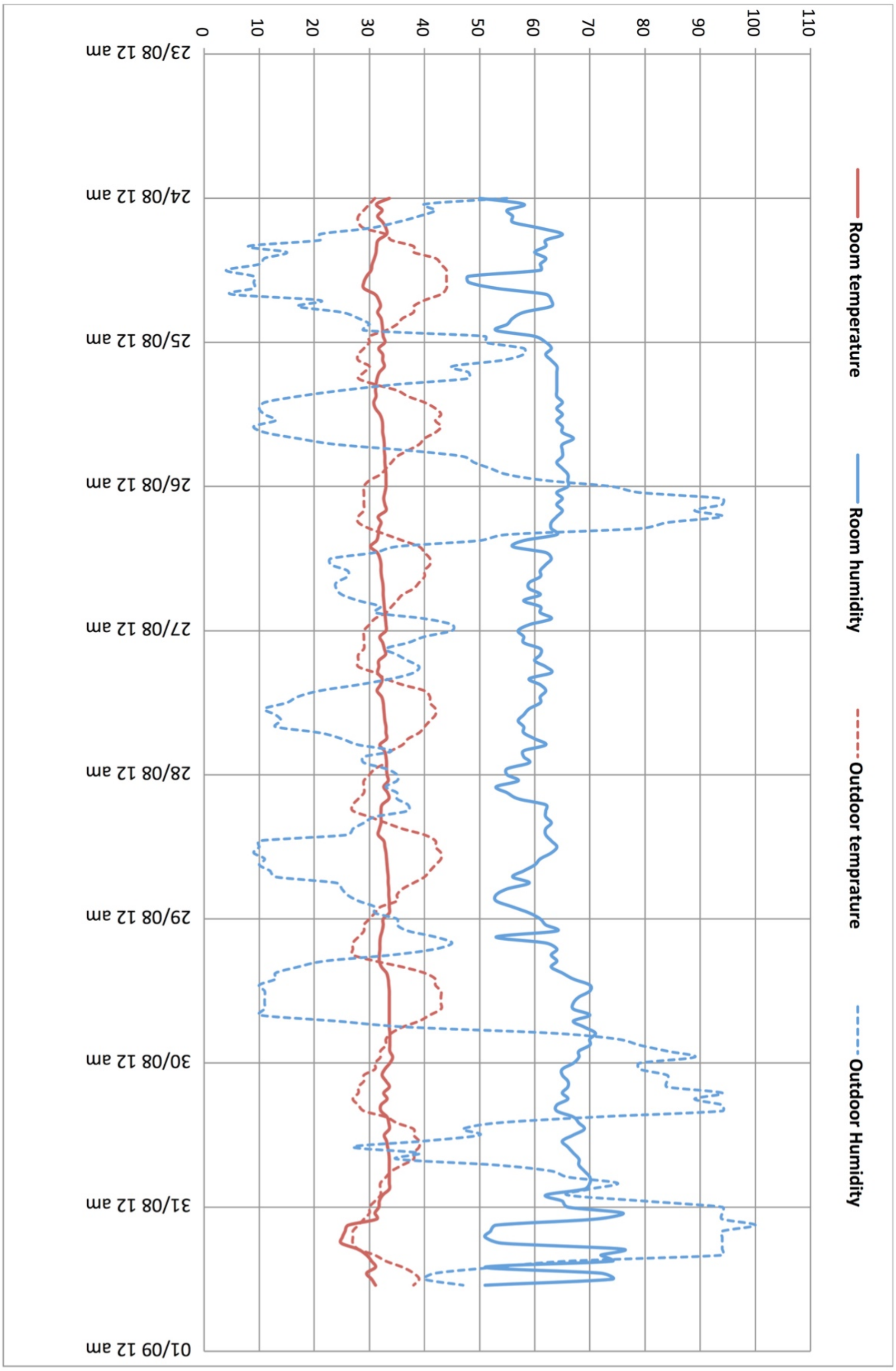
case 18.x

Timestamp	Outdoor Temperature	Outdoor Humidity	Room temperature	Room humidity	Subject	Place	Feelings vote	Preference	Humidity Feelings	Activity	Eating	Clothing	Room Control and features in operation	Open the window over 24h
25/08/2013 10:58 am	42	10	32.8	62	31	1	2	1	2	0	5	0.41	F	2
25/08/2013 11:36 am	43	11	32.5	60	30	1	2	2	2	0	2	0.59	A , F	2
25/08/2013 12:04 pm	42	13	31.7	63	29	1	4	2	2	0	1	0.77	F, D, E, A	2
25/08/2013 01:47 pm	43	9	32	56	29	2	2	1	3	0	3	0.8	D, A	2
25/08/2013 03:31 pm	40	17	34.2	56	31	2	1	2	4	1	2	0.18	A	2
25/08/2013 06:22 pm	37	37	34.9	58	29	2	1	1	2	0	2	0.18	F, E, A	2
26/08/2013 03:44 am	29	89	26	56	29	2	3	1	3	0	5	0.18	F, A	1
26/08/2013 05:16 am	28	94	26	55	31	2	3	3	4	0	5	0.18	D, A	2
26/08/2013 08:40 am	36	50	33	66	31	1	2	1	1	1	5	0.39	F, D, E, A	2
26/08/2013 10:45 am	39	35	33	66	30	1	1	1	1	0	4	0.69	F, D, E, A	2
26/08/2013 11:24 am	40	31	33	66	29	1	2	2	3	1	2	0.77	D, E, A	2
26/08/2013 02:16 pm	40	26	32.8	63	31	2	1	1	3	2	2	0.18	E, A	2
26/08/2013 07:43 pm	34	32	32.8	54	29	2	1	1	4	0	5	0.18	D, A	2
27/08/2013 03:24 am	29	33	32.4	58	29	1	2	1	3	2	1	0.77	A , F	1
27/08/2013 08:46 am	36	28	32.9	62	30	1	1	1	2	1	4	0.69	F, E, A	1
27/08/2013 10:20 am	40	21	33	59	31	1	2	1	1	0	4	0.39	F, D, E	2
27/08/2013 11:17 am	41	17	32.9	58	29	1	2	1	3	2	4	0.77	F, D, E, A	1
27/08/2013 01:09 pm	42	11	31.1	62	29	2	2	1	2	0	2	0.18	D, E	2
27/08/2013 03:27 pm	41	14	33.3	58	31	2	2	1	4	0	2	0.18	A	2
27/08/2013 09:27 pm	33	29	28.9	46	29	2	3	3	4	0	2	0.18	C, D, A	2
28/08/2013 05:20 am	27	37	33	61	29	1	2	1	4	2	1	0.77	F, D, E, A	2
28/08/2013 07:59 am	33	29	33	57	29	1	2	1	4	2	4	0.77	F, D, E, A	2
28/08/2013 10:14 am	40	26	33.1	56	30	1	1	1	2	0	5	0.69	F, C, E, A	2
28/08/2013 01:14 pm	43	9	32.5	56	29	2	2	1	4	0	2	0.18	D, A	1
28/08/2013 07:48 pm	35	26	32.8	47	29	2	2	2	4	0	1	0.18	D, E, A	1
29/08/2013 03:46 am	27	45	30.3	56	29	2	2	1	4	0	1	0.18	D, A	2
29/08/2013 08:21 am	37	17	33.6	54	29	1	2	1	3	2	4	0.77	F, D, E, A	2
29/08/2013 08:26 am	37	17	30.9	56	31	2	2	1	3	0	5	0.23	E, A	2
29/08/2013 06:46 pm	34	63	31.6	64	30	1	3	1	3	3	1	0.69	F, D, E, A	2
29/08/2013 06:48 pm	34	63	31.6	64	30	1	3	1	3	1	2	0.69	F, D, E, A	2
30/08/2013 01:28 am	31	79	30	56	29	2	3	1	1	0	3	0.18	D, A	2
30/08/2013 01:41 am	29	84	30.1	58	30	2	2	1	1	0	2	0.12	D, A	2
30/08/2013 01:42 am	29	84	30.1	58	30	2	2	1	1	0	3	0.31	D, A	2
30/08/2013 12:22 pm	38	50	33.4	65	31	2	2	1	3	0	5	0.18	A	2
30/08/2013 02:52 pm	38	39	33.6	66	31	1	1	1	1	2	1	0.9	F, E, A	2
30/08/2013 07:12 pm	33	66	32.1	64	29	1	2	1	1	2	1	0.77	F, D, E, A	2
30/08/2013 07:14 pm	33	66	32.1	64	30	1	2	2	2	1	1	0.27	F, D, E, A	2
30/08/2013 07:15 pm	33	66	32.1	64	30	1	2	1	2	0	2	0.33	F, D, E, A	2
30/08/2013 11:51 pm	30	94	27.9	51	29	2	4	1	2	0	2	0.77	F, D, E, A	2
30/08/2013 11:53 pm	30	94	28.2	60	30	2	4	1	2	1	2	0.12	F, D, E, A	2
30/08/2013 11:54 pm	30	94	28.2	60	30	2	4	1	2	2	5	0.39	F, D, E, A	2
31/08/2013 12:17 am	30	94	33.2	66	31	1	1	1	1	1	5	0.39	F, D, E, A	2
31/08/2013 01:50 am	29	94	26.8	52	31	2	4	1	3	1	5	0.32	E, A	2
31/08/2013 09:49 am	36	53	31.8	64	29	1	2	1	1	2	5	0.77	D, E, A	2
31/08/2013 09:51 am	36	53	31.8	64	30	1	2	1	1	1	5	0.39	F, D, E	2
31/08/2013 09:52 am	36	53	31.8	64	30	1	2	1	1	0	2	0.33	D, E, A	2
31/08/2013 10:37 am	38	42	27.9	67	31	2	4	3	4	0	5	0.18	A	2
31/08/2013 12:25 pm	39	40	30.7	75	29	2	2	1	2	2	1	0.18	F, D, E, A	2
31/08/2013 12:26 pm	39	40	30.7	75	30	2	2	1	2	1	5	0.59	F, D, E, A	2
31/08/2013 12:28 pm	39	40	30.8	75	30	2	2	1	2	3	1	0.69	F, D, E, A	1

Form Responses

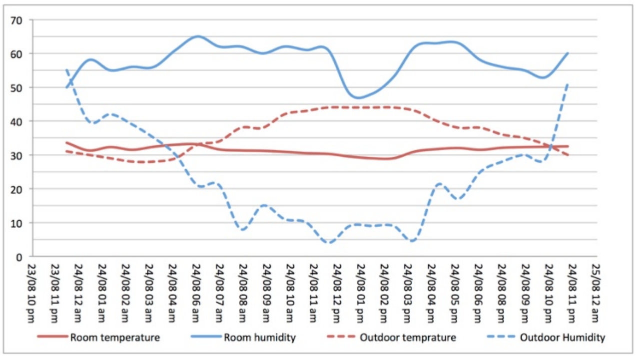
Chart1

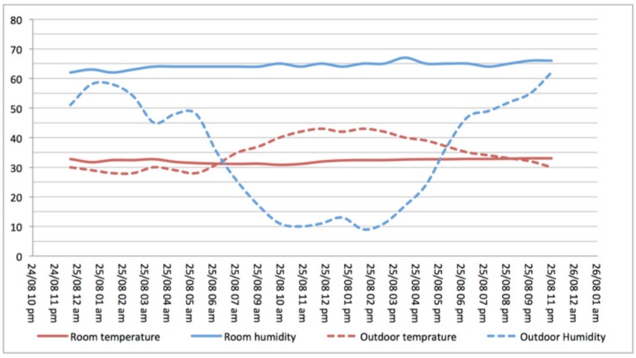
Room A

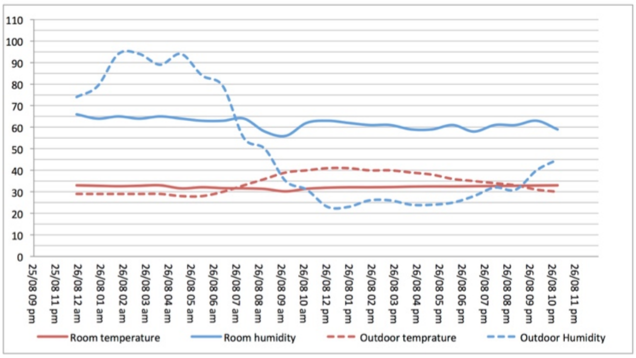


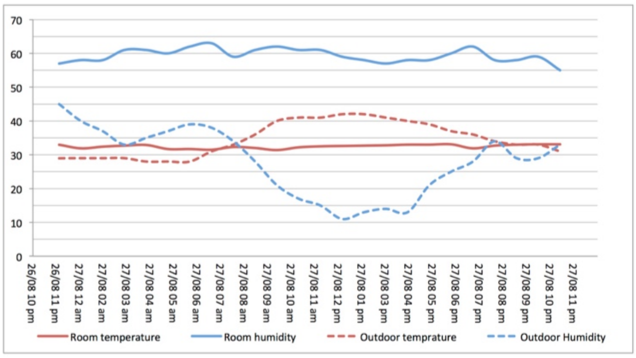
case 18.xlsx

Date & Time	Room temperature	Room humidity	Outdoor temprature	Outdoor Humidity
24/08 12 AM	33.6	50	31	55
24/08 01 AM	31.3	58	30	40
24/08 02 AM	32.3	55	29	42
24/08 03 AM	31.5	56	28	39
24/08 04 AM	32.4	56	28	35
24/08 05 AM	33	61	29	30
24/08 06 AM	33.1	65	33	21
24/08 07 AM	31.6	62	34	21
24/08 08 AM	31.3	62	38	8
24/08 09 AM	31.2	60	38	15
24/08 10 AM	30.9	62	42	11
24/08 11 AM	30.5	61	43	10
24/08 12 PM	30.3	61	44	4
24/08 01 PM	29.5	48	44	9
24/08 02 PM	29	48	44	9
24/08 03 PM	29	53	44	9
24/08 04 PM	31	62	43	5
24/08 05 PM	31.7	63	40	21
24/08 06 PM	32	63	38	17
24/08 07 PM	31.5	58	38	25
24/08 08 PM	32.1	56	36	28
24/08 09 PM	32.3	55	35	30
24/08 10 PM	32.4	53	33	29
24/08 11 PM	32.5	60	30	51
25/08 12 AM	32.8	62	30	51
25/08 01 AM	31.7	63	29	58
25/08 02 AM	32.4	62	28	58
25/08 03 AM	32.4	63	28	54
25/08 04 AM	32.7	64	30	45
25/08 05 AM	31.8	64	29	48
25/08 06 AM	31.4	64	28	48
25/08 07 AM	31.2	64	31	35
25/08 08 AM	31.1	64	35	25
25/08 09 AM	31.2	64	37	17
25/08 10 AM	30.8	65	40	11
25/08 11 AM	31.1	64	42	10
25/08 12 PM	31.9	65	43	11
25/08 01 PM	32.3	64	42	13
25/08 02 PM	32.4	65	43	9
25/08 03 PM	32.4	65	42	11
25/08 04 PM	32.6	67	40	17
25/08 05 PM	32.7	65	39	24
25/08 06 PM	32.7	65	37	37
25/08 07 PM	32.8	65	35	47
25/08 08 PM	32.8	64	34	49
25/08 09 PM	32.9	65	33	52
25/08 10 PM	33	66	32	55
25/08 11 PM	33	66	30	62
26/08 12 AM	33	66	29	74
26/08 01 AM	32.8	64	29	79
26/08 02 AM	32.6	65	29	94
26/08 03 AM	32.8	64	29	94
26/08 04 AM	33	65	29	89
26/08 05 AM	31.6	64	28	94
26/08 06 AM	32.1	63	28	84
26/08 07 AM	31.7	63	30	79
26/08 08 AM	31.6	64	33	55
26/08 09 AM	31.3	58	36	50
26/08 10 AM	30.2	56	39	35
26/08 11 AM	31.4	62	40	31
26/08 12 PM	31.9	63	41	23
26/08 01 PM	32.1	62	41	23
26/08 02 PM	32.1	61	40	26
26/08 03 PM	32.2	61	40	26
26/08 04 PM	32.4	59	39	24
26/08 05 PM	32.5	59	38	24
26/08 06 PM	32.5	61	36	25
26/08 07 PM	32.6	58	35	28
26/08 08 PM	32.7	61	34	32
26/08 09 PM	32.8	61	33	31
26/08 10 PM	32.9	63	31	40
26/08 11 PM	33	59	30	45
27/08 12 AM	33	57	29	45
27/08 01 AM	31.9	58	29	40
27/08 02 AM	32.4	58	29	37
27/08 03 AM	32.7	61	29	33
27/08 04 AM	32.9	61	28	35
27/08 05 AM	31.7	60	28	37
27/08 06 AM	31.7	62	28	39
27/08 07 AM	31.5	63	31	38
27/08 08 AM	32.3	59	33	34
27/08 09 AM	32	61	36	28
27/08 10 AM	31.4	62	40	21
27/08 11 AM	32.2	61	41	17
27/08 12 PM	32.5	61	41	15
27/08 01 PM	32.6	59	42	11
27/08 02 PM	32.7	58	42	13
27/08 03 PM	32.8	57	41	14
27/08 04 PM	33	58	40	13
27/08 05 PM	33	58	39	21
27/08 06 PM	33.1	60	37	25
27/08 07 PM	31.9	62	36	28
27/08 08 PM	32.7	58	34	34
27/08 09 PM	33	58	33	29
27/08 10 PM	33.1	59	33	29
27/08 11 PM	33.1	55	31	33
28/08 12 AM	33.2	55	30	35
28/08 01 AM	33.4	57	29	35
28/08 02 AM	32.6	53	29	33
28/08 03 AM	33.3	55	29	35
28/08 04 AM	33.5	57	28	35

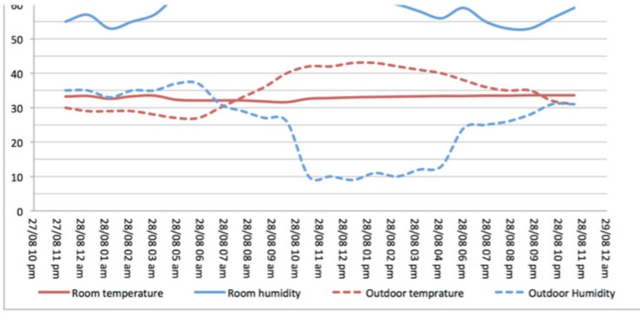


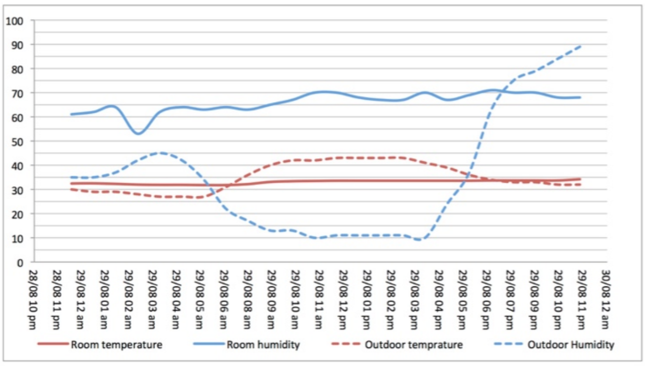


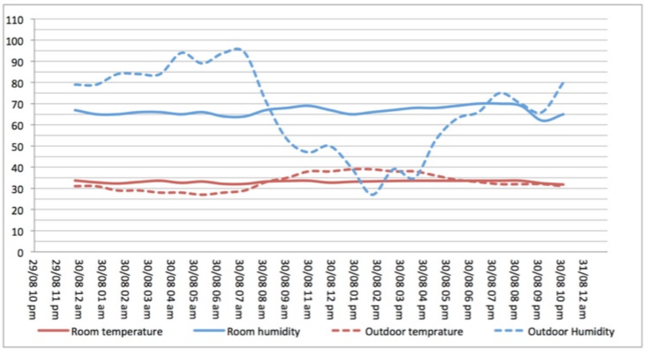


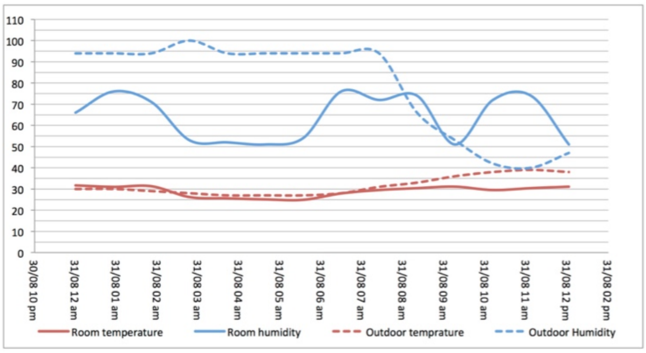


28/08 05 AM	32.3	62	27	37
28/08 06 AM	32.1	62	27	37
28/08 07 AM	32.1	62	30	31
28/08 08 AM	32.1	63	33	29
28/08 09 AM	31.8	62	36	27
28/08 10 AM	31.6	62	40	26
28/08 11 AM	32.6	63	42	10
28/08 12 PM	32.8	64	42	10
28/08 01 PM	33	63	43	9
28/08 02 PM	33.1	61	43	11
28/08 03 PM	33.2	60	42	10
28/08 04 PM	33.3	58	41	12
28/08 05 PM	33.4	56	40	13
28/08 06 PM	33.4	59	38	24
28/08 07 PM	33.5	55	36	25
28/08 08 PM	33.5	53	35	26
28/08 09 PM	33.6	53	35	28
28/08 10 PM	33.6	56	32	31
28/08 11 PM	33.6	59	31	31
29/08 12 AM	32.5	61	30	35
29/08 01 AM	32.5	62	29	35
29/08 02 AM	32.3	64	29	37
29/08 03 AM	32	53	28	42
29/08 04 AM	31.9	62	27	45
29/08 05 AM	31.9	64	27	42
29/08 06 AM	31.8	63	27	34
29/08 07 AM	31.8	64	31	22
29/08 08 AM	32.2	63	36	17
29/08 09 AM	33.1	65	40	13
29/08 10 AM	33.4	67	42	13
29/08 11 AM	33.5	70	42	10
29/08 12 PM	33.6	70	43	11
29/08 01 PM	33.6	68	43	11
29/08 02 PM	33.6	67	43	11
29/08 03 PM	33.6	67	43	11
29/08 04 PM	33.6	70	41	10
29/08 05 PM	33.6	67	39	24
29/08 06 PM	33.6	69	36	37
29/08 07 PM	33.7	71	34	63
29/08 08 PM	33.7	70	33	75
29/08 09 PM	33.7	70	33	79
29/08 10 PM	33.7	68	32	84
29/08 11 PM	34.2	68	32	89
30/08 12 AM	33.7	67	31	79
30/08 01 AM	32.8	65	31	79
30/08 02 AM	32.3	65	29	84
30/08 03 AM	33	66	29	84
30/08 04 AM	33.6	66	28	84
30/08 05 AM	32.6	65	28	94
30/08 06 AM	33.2	66	27	89
30/08 07 AM	32.1	64	28	94
30/08 08 AM	32.1	64	29	94
30/08 09 AM	33.2	67	33	71
30/08 10 AM	33.5	68	35	53
30/08 11 AM	33.6	69	38	47
30/08 12 PM	32.7	67	38	50
30/08 01 PM	33.1	65	39	40
30/08 02 PM	33.3	66	39	27
30/08 03 PM	33.5	67	38	39
30/08 04 PM	33.6	68	38	35
30/08 05 PM	33.6	68	36	53
30/08 06 PM	33.6	69	34	63
30/08 07 PM	33.6	70	33	66
30/08 08 PM	33.6	70	32	75
30/08 09 PM	33.6	69	32	70
30/08 10 PM	32.4	62	32	66
30/08 11 PM	31.8	65	31	80
31/08 12 AM	31.7	66	30	94
31/08 01 AM	31	76	30	94
31/08 02 AM	31.3	71	29	94
31/08 03 AM	26.2	53	28	100
31/08 04 AM	25.6	52	27	94
31/08 05 AM	25.1	51	27	94
31/08 06 AM	24.9	54	27	94
31/08 07 AM	27.9	76	28	94
31/08 08 AM	29.5	72	31	94
31/08 09 AM	30.4	74	33	66
31/08 10 AM	31.1	51	36	53
31/08 11 AM	29.5	72	38	42
31/08 12 PM	30.4	74	39	40
31/08 01 PM	31.1	51	38	47









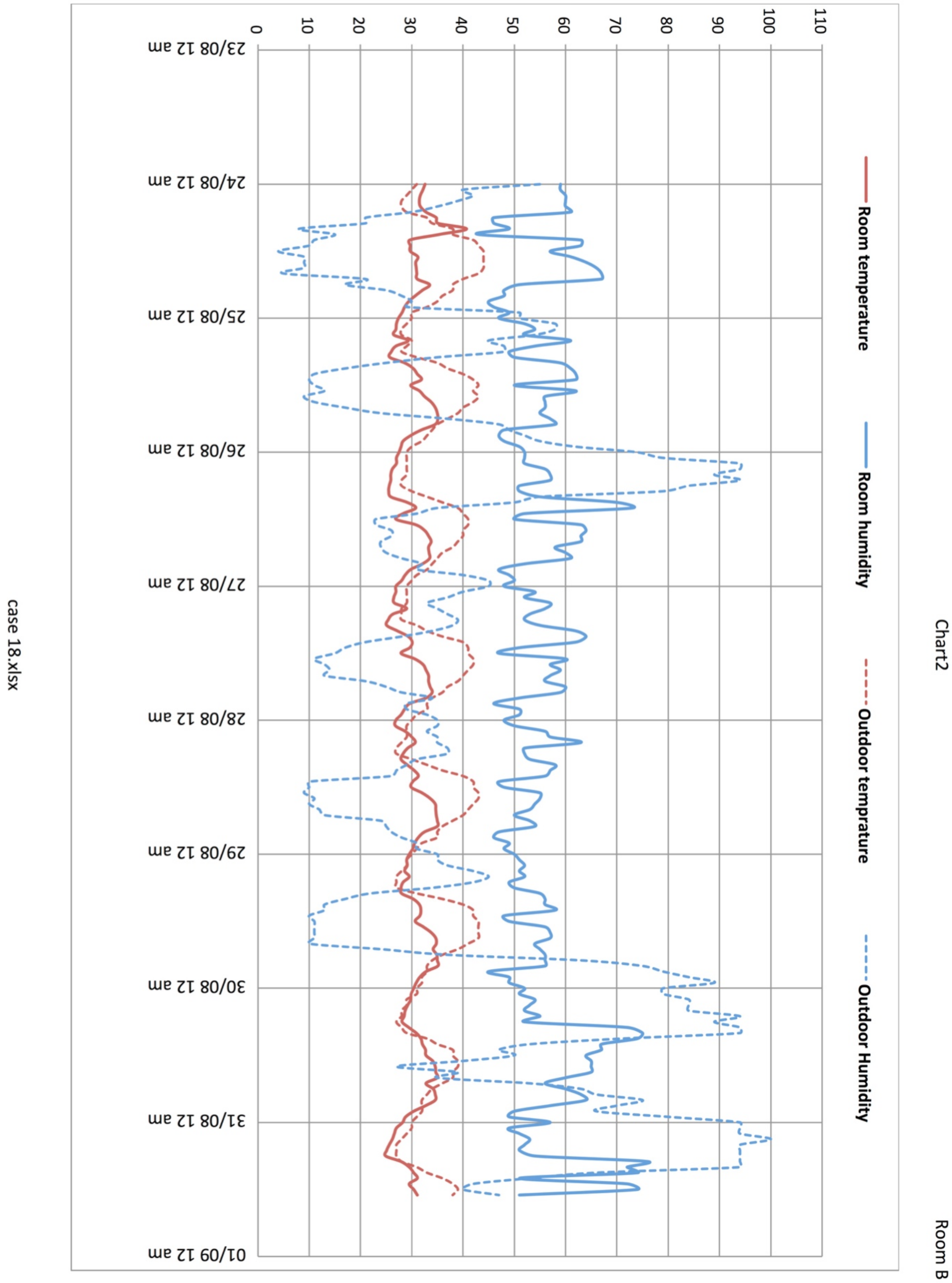
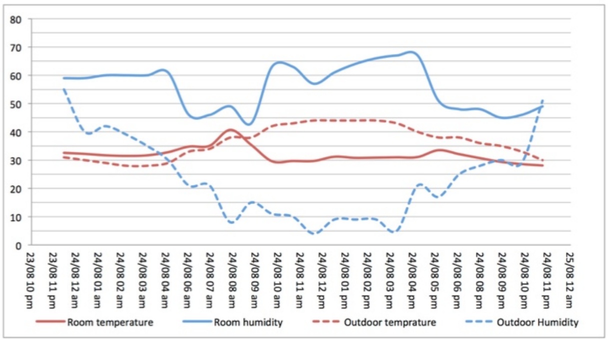
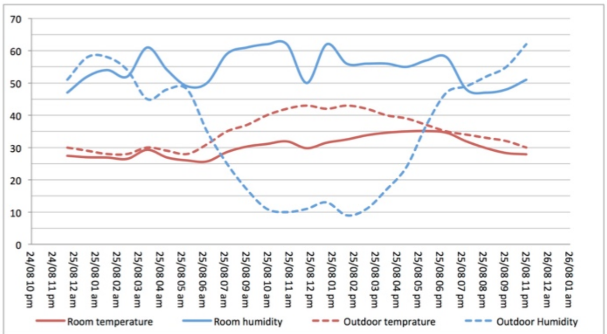
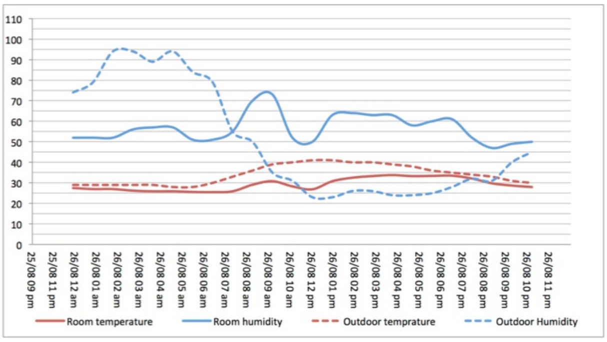


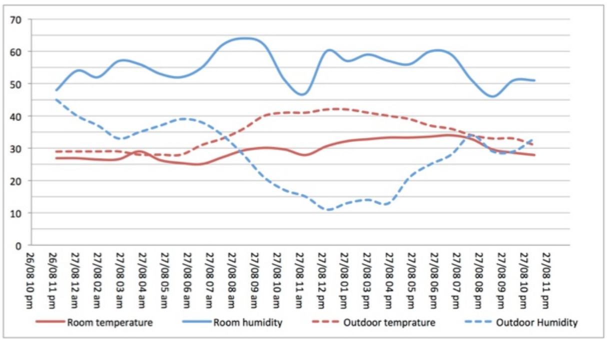
Chart2
Room B
Room temperature
Room humidity
Outdoor temprature
Outdoor Humidity
0
10
20
30
40
50
60
70
80
90
100
110
23/08 12 am
24/08 12 am
25/08 12 am
26/08 12 am
27/08 12 am
28/08 12 am
29/08 12 am
30/08 12 am
31/08 12 am
01/09 12 am
case 18.xlsx

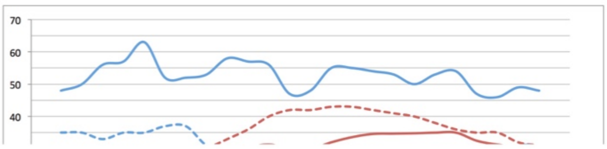
Date & Time	Room temperature	Room humidity	Outdoor temprature	Outdoor Humidity
24/08 12 AM	32.6	59	31	55
24/08 01 AM	32.2	59	30	40
24/08 02 AM	31.7	60	29	42
24/08 03 AM	31.5	60	28	39
24/08 04 AM	31.7	60	28	35
24/08 05 AM	32.8	61	29	30
24/08 06 AM	34.8	46	33	21
24/08 07 AM	35.1	46	34	21
24/08 08 AM	40.7	49	38	8
24/08 09 AM	35.4	43	38	15
24/08 10 AM	29.6	63	42	11
24/08 11 AM	29.7	63	43	10
24/08 12 PM	29.7	57	44	4
24/08 01 PM	31.2	61	44	9
24/08 02 PM	30.8	64	44	9
24/08 03 PM	30.9	66	44	9
24/08 04 PM	31	67	43	5
24/08 05 PM	31.1	67	40	21
24/08 06 PM	33.5	51	38	17
24/08 07 PM	32.1	48	38	25
24/08 08 PM	30.7	48	36	28
24/08 09 PM	29.4	45	35	30
24/08 10 PM	28.6	46	33	29
24/08 11 PM	28.1	49	30	51
25/08 12 AM	27.4	47	30	51
25/08 01 AM	27	52	29	58
25/08 02 AM	26.9	54	28	58
25/08 03 AM	26.5	52	28	54
25/08 04 AM	29.3	61	30	45
25/08 05 AM	26.9	54	29	48
25/08 06 AM	26	49	28	48
25/08 07 AM	25.7	50	31	35
25/08 08 AM	28.6	59	35	25
25/08 09 AM	30.3	61	37	17
25/08 10 AM	31.1	62	40	11
25/08 11 AM	31.9	62	42	10
25/08 12 PM	29.8	50	43	11
25/08 01 PM	31.5	62	42	13
25/08 02 PM	32.5	56	43	9
25/08 03 PM	33.8	56	42	11
25/08 04 PM	34.6	56	40	17
25/08 05 PM	35	55	39	24
25/08 06 PM	35.1	57	37	37
25/08 07 PM	34.6	58	35	47
25/08 08 PM	31.9	48	34	49
25/08 09 PM	29.8	47	33	52
25/08 10 PM	28.3	48	32	55
25/08 11 PM	27.9	51	30	62
26/08 12 AM	27.5	52	29	74
26/08 01 AM	27	52	29	79
26/08 02 AM	27	52	29	94
26/08 03 AM	26.2	56	29	94
26/08 04 AM	25.9	57	29	89
26/08 05 AM	25.9	57	28	94
26/08 06 AM	25.6	51	28	84
26/08 07 AM	25.5	51	30	79
26/08 08 AM	25.9	55	33	55
26/08 09 AM	29.1	70	36	50
26/08 10 AM	30.8	73	39	35
26/08 11 AM	28.3	52	40	31
26/08 12 PM	26.9	50	41	23
26/08 01 PM	30.8	63	41	23
26/08 02 PM	32.5	64	40	26
26/08 03 PM	33.3	63	40	26
26/08 04 PM	33.8	63	39	24
26/08 05 PM	33.3	58	38	24
26/08 06 PM	33.4	60	36	25
26/08 07 PM	33.5	61	35	28
26/08 08 PM	32.1	52	34	32
26/08 09 PM	29.8	47	33	31
26/08 10 PM	28.7	49	31	40
26/08 11 PM	28	50	30	45
27/08 12 AM	26.9	48	29	45
27/08 01 AM	26.9	54	29	40
27/08 02 AM	26.5	52	29	37
27/08 03 AM	26.6	57	29	33
27/08 04 AM	29	56	28	35
27/08 05 AM	26.3	53	28	37
27/08 06 AM	25.4	52	28	39
27/08 07 AM	25.1	55	31	38
27/08 08 AM	27.2	62	33	34
27/08 09 AM	29.3	64	36	28
27/08 10 AM	30.1	62	40	21
27/08 11 AM	29.6	51	41	17
27/08 12 PM	27.9	47	41	15
27/08 01 PM	30.6	60	42	11
27/08 02 PM	32.2	57	42	13
27/08 03 PM	32.8	59	41	14
27/08 04 PM	33.3	57	40	13
27/08 05 PM	33.3	56	39	21
27/08 06 PM	33.6	60	37	25
27/08 07 PM	34	59	36	28
27/08 08 PM	32.8	51	34	34
27/08 09 PM	29.6	46	33	29
27/08 10 PM	28.6	51	33	29
27/08 11 PM	27.9	51	31	33
28/08 12 AM	26.9	48	30	35
28/08 01 AM	26.8	50	29	35
28/08 02 AM	28.7	56	29	33
28/08 03 AM	30	57	29	35
28/08 04 AM	30.7	63	28	35
28/08 05 AM	29.2	52	27	37
28/08 06 AM	28.3	52	27	37
28/08 07 AM	27.9	53	30	31
28/08 08 AM	29.1	58	33	29
28/08 09 AM	30.5	57	36	27
28/08 10 AM	31.3	56	40	26





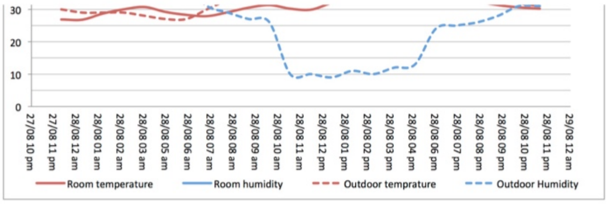


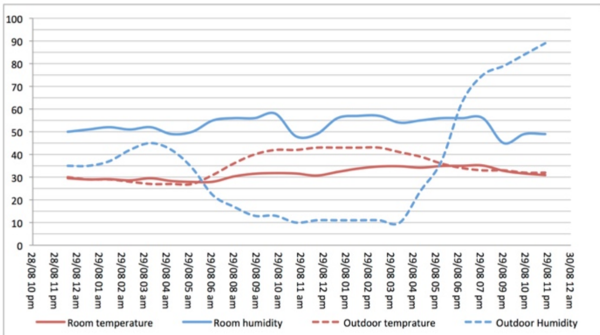


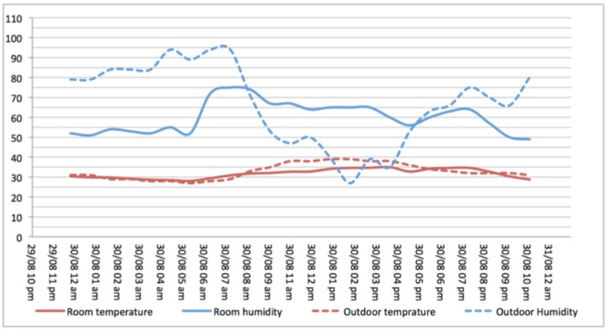


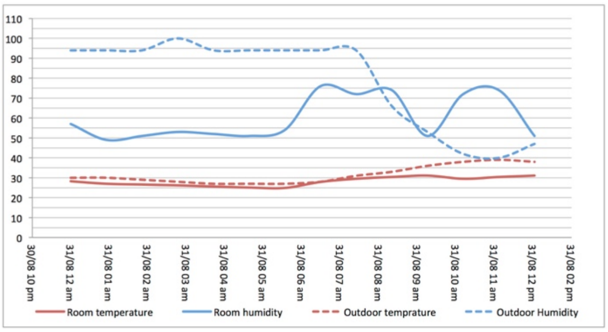
Page 2 Room B 24h

28/08 11 AM	30.2	47	42	10
28/08 12 PM	29.9	48	42	10
28/08 01 PM	32	55	43	9
28/08 02 PM	33.6	55	43	11
28/08 03 PM	34.6	54	42	10
28/08 04 PM	34.7	53	41	12
28/08 05 PM	34.8	50	40	13
28/08 06 PM	35	53	38	24
28/08 07 PM	35	54	36	25
28/08 08 PM	32.5	47	35	26
28/08 09 PM	31.3	46	35	28
28/08 10 PM	30.6	49	32	31
28/08 11 PM	30.2	48	31	31
29/08 12 AM	29.5	50	30	35
29/08 01 AM	29	51	29	35
29/08 02 AM	29.1	52	29	37
29/08 03 AM	28.6	51	28	42
29/08 04 AM	29.5	52	27	45
29/08 05 AM	28.3	49	27	42
29/08 06 AM	27.9	50	27	34
29/08 07 AM	28	55	31	22
29/08 08 AM	30.3	56	36	17
29/08 09 AM	31.5	56	40	13
29/08 10 AM	31.8	58	42	13
29/08 11 AM	31.6	48	42	10
29/08 12 PM	30.7	49	43	11
29/08 01 PM	32.3	56	43	11
29/08 02 PM	33.8	57	43	11
29/08 03 PM	34.7	57	43	11
29/08 04 PM	34.8	54	41	10
29/08 05 PM	34.2	55	39	24
29/08 06 PM	34.9	56	36	37
29/08 07 PM	35	56	34	63
29/08 08 PM	35.1	56	33	75
29/08 09 PM	32.8	45	33	79
29/08 10 PM	31.6	49	32	84
29/08 11 PM	30.9	49	32	89
30/08 12 AM	30.4	52	31	79
30/08 01 AM	29.9	51	31	79
30/08 02 AM	29.8	54	29	84
30/08 03 AM	29.2	53	29	84
30/08 04 AM	28.7	52	28	84
30/08 05 AM	28.5	55	28	94
30/08 06 AM	28.1	52	27	89
30/08 07 AM	29.4	72	28	94
30/08 08 AM	30.9	75	29	94
30/08 09 AM	31.8	74	33	71
30/08 10 AM	32.1	67	35	53
30/08 11 AM	32.7	67	38	47
30/08 12 PM	32.8	64	38	50
30/08 01 PM	34.1	65	39	40
30/08 02 PM	34.6	65	39	27
30/08 03 PM	34.7	65	38	39
30/08 04 PM	35	60	38	35
30/08 05 PM	32.8	56	36	53
30/08 06 PM	34.2	60	34	63
30/08 07 PM	34.6	63	33	66
30/08 08 PM	34.6	64	32	75
30/08 09 PM	32.7	57	32	70
30/08 10 PM	30.4	50	32	66
30/08 11 PM	28.8	49	31	80
31/08 12 AM	28.2	57	30	94
31/08 01 AM	27	49	30	94
31/08 02 AM	26.6	51	29	94
31/08 03 AM	26.2	53	28	100
31/08 04 AM	25.6	52	27	94
31/08 05 AM	25.1	51	27	94
31/08 06 AM	24.9	54	27	94
31/08 07 AM	27.9	76	28	94
31/08 08 AM	29.5	72	31	94
31/08 09 AM	30.4	74	33	66
31/08 10 AM	31.1	51	36	53
31/08 11 AM	29.5	72	38	42
31/08 12 PM	30.4	74	39	40
31/08 01 PM	31.1	51	38	47









case 18.xlsx

Appendix VI

A copy of the proceeding paper participated in Windsor Conference 2014

Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

What is the relationship between humidity and comfort at high temperatures? In search of new ways of looking at the issue

Abdulrahman Alshaikh[1], Susan Roaf[1] and Robert Smith[1]

1, Heriot Watt University, Edinburgh EH14 4AS

Abstract

This draft paper was developed as a stalking horse for the Windsor 2014 Conference workshop on Statistics, It presents the results of summer time field work undertaken by Abdulrahman Alsheikh in the region of Damman, Saudi Arabia and the data collected shows that middle class homes families there occasionally report thermal neutrality at very high temperatures and humidities. The issues surrounding the collection, analysis and understanding of the complex issues around the relationship between humidity and comfort at high temperatures has long been a difficult one and the paper sets out some general back ground, presents the preliminary findings from the Dammam field work and then raises some questions that we hope the expert statisticians running the workshop can help us make sense of, with a view to publishing a full paper subsequently including the results of the workshop deliberations.

Keywords: PMV, Thermal Comfort, High Temperatures, Humidity

1. Introduction

Where the temperature and humidity are both high, humidity came to be seen historically as a potent force for discomfort. Many of the early developments in heating and cooling systems that were devised to reduce humidity were instigated to improve the efficiency of manufacturing processes in hot climates and also in response to the very poor standard of building construction, particularly in cold climates. On cold damp days in buildings with thin walls that were almost the same temperature on the inside as the outside, large families gathered in wood gas or coal heated rooms resulted in damp walls and mould the health and well-being of building occupants.

John Gorrie, a pre-eminent pioneer of air-conditioning who lived and worked in Florida focussed on temperature rather than humidity in his work in his designs for cooling systems using 'mechanical condensation' that began as early as 1854 [i]. Many subsequent buildings were cooled with ice placed in the air supply ducts but by 1918 Alfred Woolff, Stuart Cramer and Willis Carrier, doyens of the US heating, ventilating and air-conditioning (HVAC) industry had all built mechanical ventilation systems that incorporated humidity control to improve indoor comfort. By this stage US designers had identified humidity as a primary cause of summer discomfort and air-conditioning systems were increasingly designed not only to cool the air but to manage its humidity. Wolff concluded that 55% RH was the optimal level to strive for but such conclusions were based on little evidence. The consequence of this assumption was to push systems to use a two phase cooling systems, first chilling down the air to remove humidity by condensation and then to heat it up so further reducing its relative humidity – but only at the cost of significant energy inefficiency to get air to the required temperature.

Tradition held that cold damp weather chilled one to the bone while hot humid days made people feel sickly and uncomfortable. Today the average US worker takes one day a month off due to Sick Building Syndrome but this is a condition, that research leads us to believe, is affected by humidity but results from inadequate ventilation, chemical contaminants from indoor or outdoor sources, and/or biological contaminants.

However a key symptom of the use of air-conditioning systems is the drying of indoor air that can typically be as low as 10%-35% RH causing a range of SBS symptoms and discomfort. However it has been found that increasing humidity in such dry buildings to above 40% has no measurable impacts on occupant heath [ii]. But if the core concern is occupant comfort, the subsequent century of research has often contributed to the confusion of the actual role and impact of humidity on the experience of comfort at high temperatures [iii].

A wide range of 20th Century tropical comfort indices were developed based the results of field studies and laboratory studies [iv] linking humidity to comfort in a single measure such as those developed by Webb [v], Sharma [vi] and others. In 1973 Nicol and Humphreys presented the results of field studies in the UK, India, Iraq and Singapore [vii] with result showing that mean comfort vote changes little with the mean temperature experienced[viii]. A number of meta-analyses of the role of humidity in comfort in tropical regions have been undertaken including that by de Dear et al [ix]. Numerous recent field studies have often shown that comfort in tropical regions is experience with high humidity and temperatures when compared with Western standards for comfort [x].

In order to clarify the issues involved in our own minds we are bringing the following recent Dammam region case study to the Windsor 2014 conference for a discussion of how we might use statistics better to unravel the complex relationship between humidity and comfort at higher temperatures. Data collection and results were produced by Abdulrahman Alsheikh and the whole underlying data set was supplied to Rex and Jane Galbraith prior to the W14 Conference. They were asked to review the approach, limitations and opportunities presented by this study, during discussion at the Windsor Workshop on Statistics.

2. The Damman Case Study methodology

The Dammam field surveys were undertaken using a standard longitudinal thermal sampling in air-conditioned houses in the city of Dammam, Saudi Arabia. The survey involved 17 homes distributed in the eastern region of Saudi Arabia and was carried out from 10th to 31st of August 2013 during the hot season. Subjective data were collected through parallel questionnaires, which were completed during almost two weeks for each house over the day when the subjects were at home. The survey was completed with about 480 votes, the total subject group was 35 people and the gender split was eighteen to seventeen, males and females respectively. The ages of the subjects ranged from 21 to 60 years with a mean age of 34 years old. All subjects were in good health.

This study used air temperature as its principal physical variable. Air temperatures were obtained using small data loggers that collected and stored results automatically in an optional strain choice. The data loggers were fitted in two different places in each house, in the living rooms and bedrooms, and automatically measured indoor temperature and relative humidity. The positions of the data loggers were located to minimize heat from direct radiation, either from mechanical or human sources. Measurements of the environmental data were taken every five minutes and each volunteer was asked to vote at least twice a day. The survey was designed by the researcher to be operable in all smartphones platforms, making it easier, and more enjoyable, for subjects to vote during day/night time and in any situation.

The questionnaires contained four main sections and also requested personal information from subjects. The sections involved: thermal sensation, using a seven-point ASHRAE scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot); metabolic rate, clothing and individual's adaptation in a specific time and occupied room. The thermal scale and other sections of the questionnaire were translated into Arabic. As the culture and religion is taken into account, Values of clothing insulation were mainly derived from Al-ajmi et al. (2008) as well as from clothing values used by Nicol et al. (2012). The metabolic rates given in ISO 7730 cited in (Nicol et al., 2012) were used in this study.

3. Results and Discussions

During the fieldwork in August the indoor air temperatures ranged from a low of 19.9°C to 35.3°C with an average of around 27°C [Figure 1]. A single high report of 39.3°C was recorded in a unique event of one of the cases.

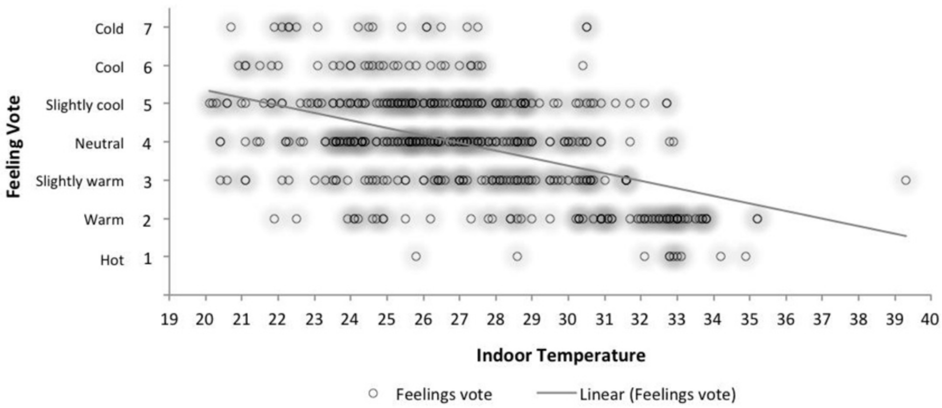


Figure 1: Distribution of indoor temperature from longitudinal survey in Dammam Region during Summer 2013.

The recorded humidity fluctuated from a low of 29% to a high of 84% with an average of around 60% relative humidity [Figure 2]. The mean clothing values were 0.42*clo* with minimum of 0.05*clo* and maximum of 0.97*clo*. About 60% of subject's clothing values were in the scope of 0.05*clo* and 0.41*clo*. The mean metabolic rate was 0.67*met* during the hot season.

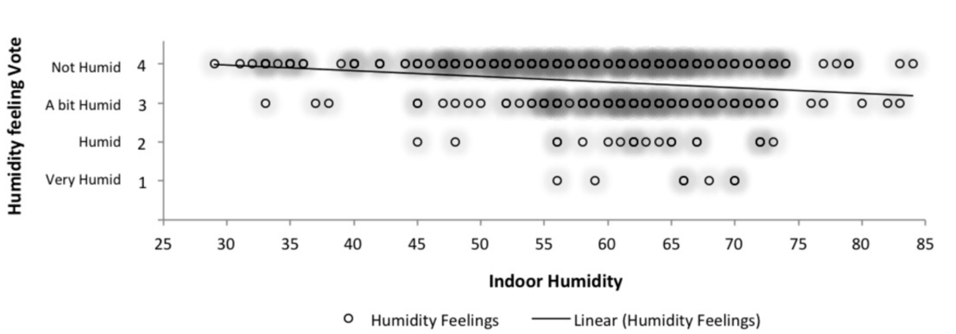


Figure 2: Distribution of indoor relative humidity from longitudinal survey in Dammam Region during Summer 2013

The analysis of the sensation votes show that about 65% of subject votes in indoor conditions indicate one of the four top categories, between Hot and Neutral, and the mean sensation votes for all subjects on the ASHRAE scale were 3.32 (Slightly warm). Furthermore, almost the same portion of subject's votes indicated they wanted more cooling to be more comfortable which shows that people are not very satisfied with their environment conditions [Figure 3].

It is obvious to ask why, if these people did not feel comfortable, don't turn on or up the AC to be more comfortable. One question in the survey been asked of all subjects that in comparison to the monthly income, do you think that the electricity bill is expensive? About 65% of the subjects responses were the price is expensive compared to their incomes.

In exploring the subject's preferences data in [Figure 3] the data shows that it is fairly robust. However, the next step will be to investigate what are the boundary conditions around these outliers votes. There were in certain circumstances some votes in warm conditions asking to be a bit warmer. A preliminary analysis shows that people who prefer to be in warmer conditions, even in the range of 29-35^{o}C, quite feel cool and are less active. Also a couple of subjects were underweight. Subjects aged between 15-20 years old voted at these temperatures for warmer conditions.

Other outlier votes showed that people in a pretty cool conditions desire to be in cooler state. Data showed that this cohort were all in the bedroom and about 90% of them were overweight. Moreover, one specific house showed a substantial portion of these outliers, so more investigation in this case is needed. In this specific outlier home it appears that those who voted to be 'a bit' or 'much' cooler, occupied indoor humidity levels above 55% and below 80%. Thus, further statistical analysis is required to understand the relationship between humidity and temperature and comfort in these studies.

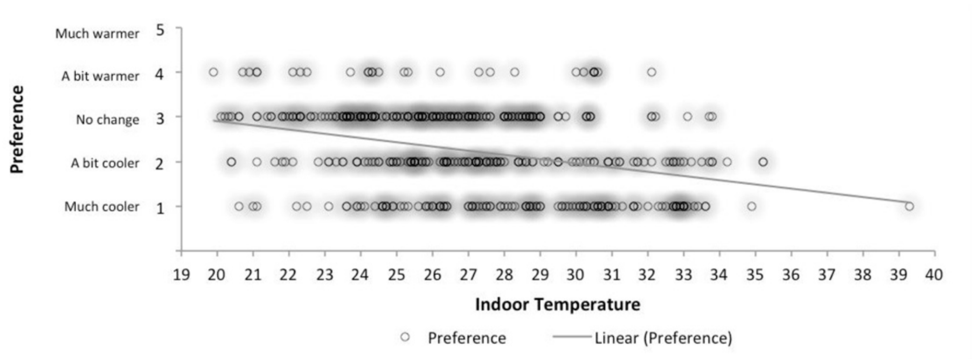


Figure 3: Regression of indoor temperature on people preferences

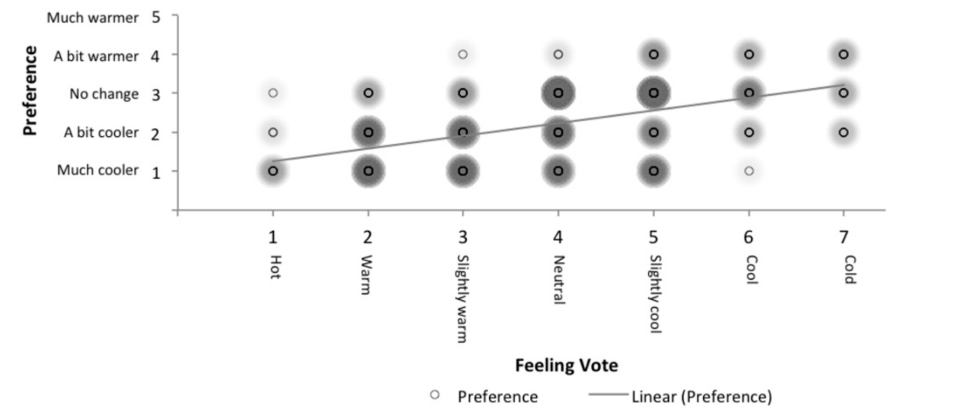


Figure 4: Regression of subject's sensation votes on their preferences

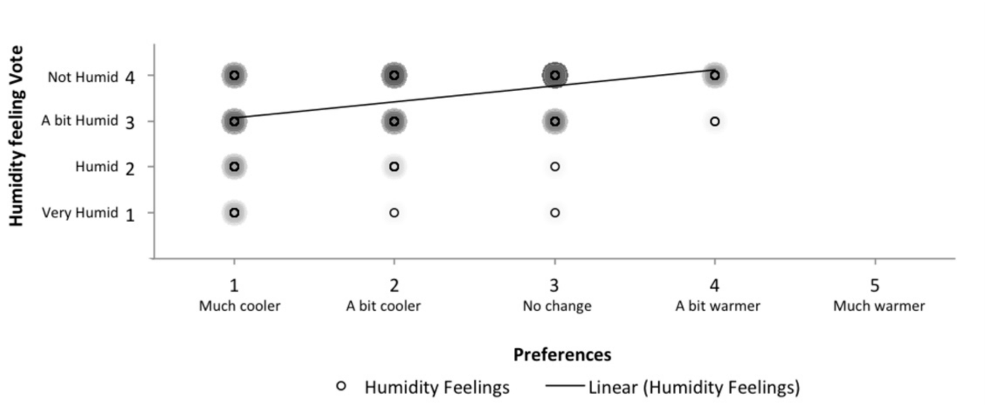


Figure 5: Regression of the subject's humidity feeling votes on their preferences

A number of questions are raised about the ability of a standard longitudinal study of comfort in extreme conditions where multiple adaptive strategies are employed to ensure occupants remain comfortable over the day. These include:

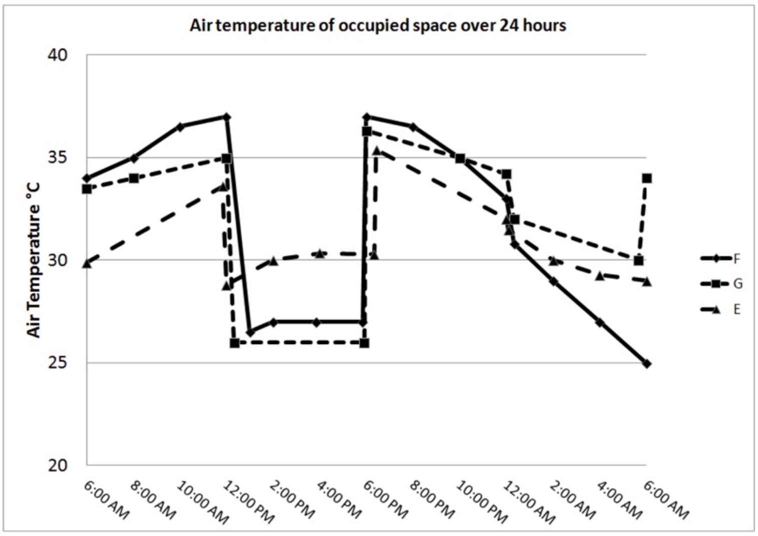


Figure 6: Temperatures occupied by housewives in the houses in the hot dry desert city of Yazd in Iran showing the wide range of thermal environments occupied over a single typical day (S.Roaf 1989[xi]).

How best can we deal with the outlier data points when they show people being comfortable at extremely high temperatures? Lifestyle observations and person centred thermal records are necessary to understand the adaptive behaviours that are used to mitigate the impacts of high temperatures experienced at different times of the day and year with building occupants:

a) getting on with their usual lifestyles as ambient temperatures ramp up or down over a day, until a certain temperature level is reached at which point they occupants change their clothing, activities, location, turn on/off a machine or open/close a window. This ramping effect and the transition temperatures (and humidities ?) are recorded by observation, not analysis of data sets.

b) moving from one location people can go from one state – eg. cool in a basement in Yazd (Figure 6) into a hot environment, cruising physiologically on stored coolth for a subliminally calculated safe period of time. This scavenging and storing of heat or cold, to enable people to occupy uncomfortable and/or unsafe thermal environments for intermittent periods within the well-trodden thermal pathway of a habitual lifestyle in extreme climates is common practice. The diverse thermal environments habitually occupied over a day, or over more extended periods, are not typically collected in longitudinal field studies but are key to understanding how comfort is thus achieved.

In trying to understand the complex interaction between humidity and comfort at high temperatures we are looking for help in the Statistics Workshop in exploring how we can systematise the recording of data to enable us to understand and compare the different behaviours associated with achieving comfort in such conditions and also in analysing the data in such a way that we can extrapolate from that data the key characteristics of the relationship between humidity and comfort at high temperatures.

4) Conclusions

We very much welcome the opportunity to share this data with the experts at Windsor to learn from the discussions more about this complex and yet extremely important issue.

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A copy of the proceeding paper participated in Windsor Conference 2016

Proceedings of 9th Windsor Conference: ***Making Comfort Relevant***
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Designing Comfortable, Low Carbon, Homes in Dammam, Saudi Arabia: The Roles of Buildings and Behaviours

Abdulrahman Alshaikh and Susan Roaf

Heriot Watt University, Edinburgh, United Kingdom. Corresponding author: ama81@hw.ac.uk

Abstract

The present paper explores the thermal performance and comfort levels of seventeen air-conditioned homes monitored during the summer of 2013 in Dammam, Saudi Arabia. The comfort of occupants was assessed using the adaptive thermal comfort method. Neutral indoor air temperatures were, in several cases, surprisingly high. Most of the studied homes do not represent thermally comfortable homes as defined within either PMV or adaptive comfort limits. The study reviewed a wide range of factors that might strongly influence neutral temperatures indoors including the properties of dwellings, occupant's behaviours and attitudes towards high energy demand, loads and costs. This paper outlines the findings of that study and draws conclusions on individual design features of the studied homes that contribute to the comfort and discomfort experienced in Dammam's dwellings during the extreme summer weather. In late 2015 The Saudi Government hiked the price of domestic energy bills by 60% as a result of low oil prices, putting pressure on ordinary families to economise in their day to day living expenses. The lessons learnt from this study are discussed in relation to the challenge of maintaining comfort in Dammam's homes while reducing energy used for cooling them.

Keywords: Thermal comfort; architectural characteristics; hot humid climate; air-conditioned homes; residential energy consumption

1 Introduction

Summertime indoor conditions in Dammam's homes are of increasing concern, due to the potential for increased discomfort and higher energy costs resulting from more extreme outdoor weather. Temperatures as high as 35°C are occupied in Dammam's dwellings despite the ease with which indoor temperatures can be lowered instantly by adjusting the air conditioning (AC) system. During summer, outdoor and indoor discomfort are exacerbated during extreme hot spells, particularly when dust storms occur that prohibit the use of natural ventilation and the reduce the efficiency of AC systems. The rise in the occurrence of abnormally hot spells experienced in the region during summers and the transition seasons signal the emergence of acclimate that is less predictable and more adverse throughout the year (Tanarhte et al. 2015). Consequently, rising indoor temperatures driver higher levels of discomfort which in turn puts a growing financial burden on families impacting adversely on their lifestyles and standards of living. Similar pressures were key drivers in the collapse of the US and subsequent global economies in 2007 when American homeowners found that rising energy bills meant they could not longer pay their mortgages, providing some evidence that if not dealt with this too could be a major problem for Saudi Arabia (Roaf, 2014). Since the last world economic crisis, the cost of living has risen remarkably in the region putting households under increasing financial strain to spend more while the income levels remain the same (Albaaz, 2008), with the rising cost of electricity over the last decade making up a considerable portion of the growing wedge between lifestyle aspirations and affordability.

Since all the contemporary Saudi buildings have been primarily designed to be cooled by artificial systems (Eben Saleh, 1998) the region is now recognised as having an AC dependent society (Elsheshtawy, 2008), a fact responsible for the very high comparative levels of energy consumption especially in homes. Furthermore, account needs to be taken of the fact that the historically low energy prices in Saudi Arabia have encouraged higher energy demand by consumers (Alyousef & Stevens, 2011). Over the past decade, there has been a dramatic increase in the use of electricity in the residential sector in Saudi Arabia, accounting now for around 50% of the total Saudi electricity consumption (MOWE, 2012). As there are projected to be 2.32 million further new dwellings in the Saudi market by 2020 (Ahmad, 2002), an significant increase in the electricity supplied for residential buildings will be needed in the coming years just to provide adequate indoor conditions in the building stock. Low awareness of energy and environmental issues, evidenced also in this study, leads also to more demanding and energy-intensive lifestyles. A December 2015 60% hike in Saudi Arabian domestic energy prices will disproportionately affect energy costs in low-performance homes, which consequently will put pressure on some families' budgets for those striving to maintain and affordable the comfort temperature in their homes.

This paper is based on the results of summer time fieldwork undertaken in seventeen homes in Dammam, the capital city of the eastern region of Saudi Arabia, a city with a well-established and growing population, designed to explore such issues on the ground. This study was conducted in three parts: a standard thermal comfort field study established those temperatures at which people reported thermal neutrality in their homes during very hot summer periods. The second part covers an investigation of the characteristics of the house occupants and their behaviours and attitudes towards their own homes. The third section details a physical review of the homes, their services and physical contexts and conditions. It was felt necessary to understand all of these aspects of the homes in order to get a clearer understanding of how their comfort 'ecosystem' worked in practice and develop the evidence from which could be drawn useful practical lessons for contemporary designers in the region. This paper outlines the findings arising from the study of the relationship between the physical design features of the Dammam's homes, and reported comfort, energy consumption and energy costs in the homes.

2 The Field Work Methodology

The Dammam field work was undertaken using a standard longitudinal thermal sampling method (Nicol, Humphreys, & Roaf, 2012) in seventeen air-conditioned homes. The survey involved dwellings that occupied by middle-class families with an average of six people in each home, distributed within a radius of 14 miles within the city. The field measurements and survey were carried out between the 10th to the 31st of August 2013 during an extremely hot season.

This study measured air temperature as its principal physical variable. Air temperatures and relatively humidity were obtained using (KG1001) data loggers that collected and stored

[1] Temperature accuracy +/-1.0°C under 0-50°C; Humidity accuracy +/-4% under 20-80%

results automatically in an optional strain choice. The data loggers were fitted in two different places in each dwelling, in the living rooms and the main bedrooms. The positions of the data loggers were located to minimize heat from direct radiation, either from solar radiation, material, mechanical or human sources with a proper distance implemented between the subjects in their normal physical places. Measurements of the environmental data were collected every five minutes.

The researcher developed a software for the comfort survey called "*ComfApp*" which includes twelve questions operable in all smartphones platforms, making it easier, and more enjoyable, for subjects to vote during day/night time and in any situation in those rooms. As the environmental variables were being recorded concurrently, each volunteer was asked to vote at least twice a day and all of the subjects used the smart phone platform to record their thermal sensation vote. The subjective data were collected over an average of ten days for each household at regular intervals of around eight hours between each vote over the day.

Furthermore, face-to-face questionnaires were undertaken to investigate the characteristics of the dwellers and their behaviours and attitudes towards their homes, such as number of hours/day spent indoors and the use of mechanical ventilation. Questions were also included related to general information about the design and construction of the dwelling. Seeking more in-depth information, semi-structured interviews were carried out for numerous cases, in order to identify specific information that could be compared and contrasted with information gained in the other case study homes. To do this, the interviews were comprised of open-ended questions included to explore occupant's attitudes and thoughts on the energy performance of their own home, including, for example, factors that influenced their choices to operate a fan or AC rather than open a window. The following sections describe the results of this field study and conclude with discussions on those findings.

3 The Experienced Temperatures and the Reported Thermal Neutrality

The temperature variation recorded during the fieldwork, as shown in Figure 1, ranged between just below 20°C to an unoccupied outlier room temperature of 47°C. Figure 1 has an illustration of a scatter plot of the whole set of the indoor and outdoor temperature recorded during August 2013 in these dwellings. Perfect temperature control could not be expected especially when all of the dwellings had operated different HVAC systems quite possibly with different temperature set points. The mean temperature of the whole sample is 27.2°C, a figure that appears to be well above the European guidelines of maintaining interior temperatures of between 22°C and 24°C. The scatter diagram of the ASHRAE adaptive standard of 80% and 90% acceptability limits of the whole set of measured indoor and outdoor temperatures (Figure 1) indicates that people in Dammam do live in what inhabitants of many other regions of the world would classify as very hot conditions. Surprisingly, 22% of the occupied temperatures that coordinated with thermal sensation votes were above 30°C.

The measurements taken in the summer of 2013 illustrated in Table 1, moreover, provide a valuable insight into the range of mean indoor relative humidity (RH) experienced in the study homes from 41% to 72% RH. These variations might be due to individual houses having different humidity distributions that result from the behaviours of the occupants (cooking, cleaning bathing, use of dehumidifying HVAC etc.) which will modify the humidity.

The mean RH of the whole sample, of almost 60% appears to be higher than the optimal standard of 55% followed as a rule of thumb by HVAC engineers for so long.

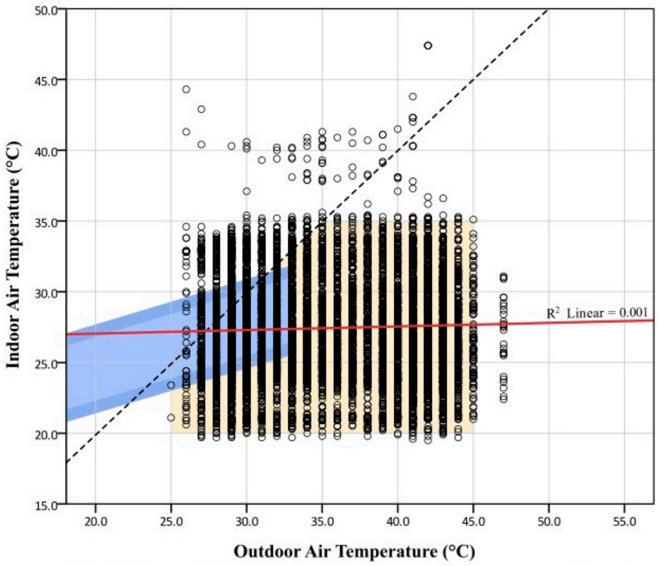

Figure 1 Scatter diagram of the ASHRAE adaptive standard of 80% and 90% acceptability limits of the whole set of indoor and outdoor temperature measured in Dammam's dwellings during the hot season, where the mean indoor and outdoor air temperatures were 27.4°C and 35.4°C respectively.

As the mean indoor air temperature in these homes range between 20°C to 35°C, it is evident that people live in a widely varying range of indoor temperatures, and that they accommodate them in the ordinary course of their day-to-day lives in their homes. Taking into consideration, the responses of all these houses, the thermal sensation votes have significant ($\alpha < 0.015$) positive weak correlation of 0.576 with the corresponding mean indoor temperatures, which indicate that the subjects are adapting to the mean indoor temperatures.

4 Occupant's behaviour

To explore the occupant's behaviours, the questionnaire used in the study interrogated the respondent's behaviours using a distributed survey that garnered four hundred and seventy-two votes from a total number of thirty-five subjects with a gender split of eighteen males and seventeen females. The ages of the subjects ranged from twenty to sixty years, with a mean age of 34 years old. All subjects were in good health during the time of the questionnaires. Calculation of their body mass indices showed that 72% of the subjects were overweight. On average the users stayed indoors at home around twelve hours per day, with women spending on average four hours more there. When asked about their electricity bills, more than the half (57.6%) of the participants replied that they often have high bills during summertime that ranged between £90 to over £200 per month. Despite the fact that the cost of a kWh of electricity delivered to the householder is ranging from only a penny to 29p for the highest consumer, around 62% reported that they considered their electricity bill was overpriced and inflated.

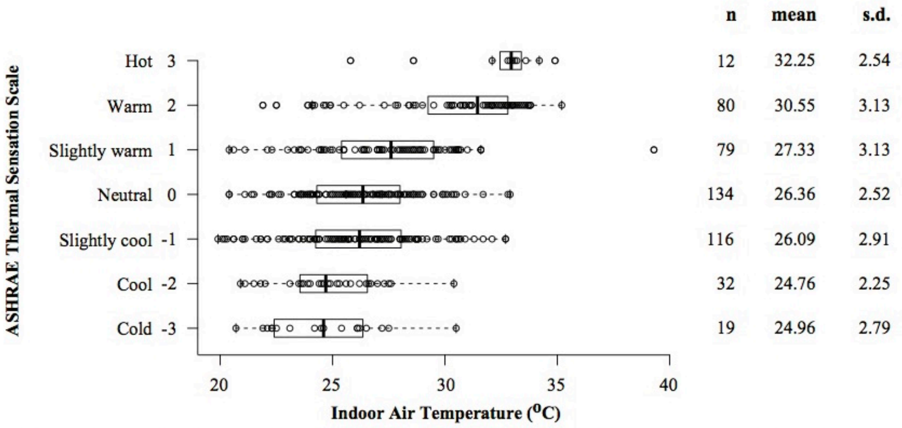

Figure 2: Boxplots and dot plots of ASHRAE thermal sensation (ASHRAE seven-point scale), and on the right hand scale a statistical summary of the indoor air temperatures associated with those ASHRAE votes (°C).

Table 1 shows the variation of all measured thermal sensations of the occupants who have a neutral pint of 0.1. From Figure 2 we can see that of the total 472 valid responses, 134 occupants described themselves as being thermally neutral. 79 respondents were slightly warm and 116 were slightly cool. 143 of the responses, or 27% of the dataset, reported being warm or hot, or cool or cold, (responses of 2, 3, or -2, -3) at the time they recorded their comfort vote. Interestingly, 92 of the respondents, or close to 20% of the dataset, were feeling warm or hot and half of these votes were experiencing a temperature equal or above 30°C. Moreover, around 20% of the latter responses preferred no change on the thermal preferences scale. The standard deviations of the thermal sensation in Table 1, furthermore, provide additional insight into how the perceptions of conditions in different houses vary, clearly influenced by the prevailing indoor temperatures.

During the longitudinal survey, occupants were asked to indicate what environmental controls were activated during the survey voting period. The adaptations noted among the controls include the use of AC, fans, windows and doors. Table 1 lists the mean and standard deviation of the control of AC and fans as well as the opening of windows and doors between the survey votes for all the dwellings. Surprisingly, only 17% of the total observations recorded occupants closing the AC system off at some point during the day of the vote. It indicates that the decision to shut down the AC system was seldom made and in some homes, it was never turned off. The main reasons for shutting the AC system were that the AC was not blowing cool enough cooling due to an over-long operation period, or because some occupants desired to be in the warmer conditions that resulted. However, the length of operation of the mechanical systems of homes in the region may reflect the low price of electricity in Saudi Arabia then. As domestic prices rise it will be interesting to see if the operation period of the mechanical systems is shortened to save money. The use of fans, moreover, were limited to seven dwellings only, and the mean value of operating the fan in those dwellings varied from 0.03 to 0.50. In those dwellings people were found to prefer to have some local air movement a one occupant reportedly preferred the cooling sensation resulting form the use of fans over those provided by activating the AC.

Table 1 The mean and standard deviation of all measured indoor air temperatures (T_a °C), Relative humidity (RH%) and the ASHRAE thermal sensation scale, besides the proportion of AC, fan, window and door's activation in all the seventeen Dammam's dwellings during summer 2013 (N: sample size; SD: standard deviation)

Dwelling #		T_a		RH		ASHRAE		AC		Fan		window		door	
	N	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	34	25.8	2.7	52.2	12.3	-1.1	1.5	0.88	0.33	0	0	0	0	0.26	0.45
2	32	27.3	2.8	64.6	6.7	-0.9	0.7	0.91	0.30	0.03	0.18	0.03	0.18	0.53	0.51
3	21	26.8	1.8	54.1	5.1	-0.5	0.7	1	0	0	0	0	0	0.10	0.30
4	28	28.8	2.1	65.1	6.8	0.4	1.3	0.64	0.49	0	0	0	0	0.61	0.50
5	39	27.5	1.9	62.4	3.7	-0.1	0.9	0.72	0.46	0	0	0	0	0.28	0.46
6	18	30.4	3.3	59.3	6.0	1.4	1	0.50	0.51	0.50	0.51	0.11	0.32	0.39	0.50
7	36	24.1	1	58.4	8.6	-0.3	1.1	0.89	0.32	0.06	0.23	0	0	0.28	0.45
8	25	26.8	3.3	64.8	7.6	0.4	1.2	0.96	0.20	0.04	0.20	0	0	0.16	0.37
9	23	22.5	1.7	65.0	5.8	-0.6	1	0.96	0.21	0	0	0	0	0.17	0.39
10	18	26.7	4.4	67.8	7.6	0.5	1	1	0	0	0	0	0	0.33	0.49
11	17	28.6	2.9	59.1	4.2	0.4	1.2	0.94	0.24	0.35	0.49	0	0	0.35	0.49
12	35	23.2	1.9	62.9	3.8	0.4	1.2	0.86	0.36	0.03	0.17	0	0	0.49	0.51
13	26	28.6	2.8	52.3	2.6	-0.2	1.5	0.77	0.43	0.23	0.43	0	0	0.62	0.50
14	27	28.2	2.3	41.3	7.9	0	1.1	0.56	0.51	0	0	0	0	0.85	0.36
15	50	31.6	2.1	60.5	6.1	1.8	0.9	0.92	0.27	0	0	0.04	0.20	0.58	0.50
16	22	27.7	2.7	55.7	8.5	-0.4	1.1	0.91	0.29	0	0	0	0	0.14	0.35
17	21	27.7	2.2	72.6	6.1	-0.6	1.8	0.76	0.44	0	0	0	0	0.52	0.51
Total	**472**	**27.2**	**3.4**	**59.7**	**9.6**	**0.1**	**1.4**	**0.83**	**0.37**	**0.06**	**0.23**	**0.01**	**0.10**	**0.41**	**0.49**

Although all of the surveyed dwellings have operable windows, almost a nil proportion (1%) of occupants operated the windows during the day and those were found in only three of the dwellings. In the other dwellings, windows were fully closed during the heat of the summer but opened at cooler times of the year. However interestingly the doors which opened into uncooled indoor or semi-outdoors areas were often constantly in operation, (10% - 85% of the time) in all dwellings with a mean value of 0.41. The decision to open internal doors to stimulate air movement around the house instead of windows to the outside was perhaps due to the preconception of the adversity of the outdoor condition (i.e. high humidity, temperatures and dust storms) making the opening of internal doors always a more effective choice.

5 A physical review of the homes, their services and physical contexts and conditions in relation to comfort experienced in them

Levels of comfort experienced in the homes, and the extent of adaptations required to achieve that comfort, were patently influence by the design of the individual house itself. The form, orientation, envelopes and construction of the dwellings and their HVAC systems differed substantially from each other as a result of being randomly selected (Table 2) to represent a broad corpus of homes in the region. All homes were differently planned. Some homes had envelopes with very high thermal integrity, high levels of insulation, double-glazing, minimal thermal bridging and efficient HVAC systems. Others had minimal or no insulation, single glazing, air leaks, thermal bridges and inefficient cooling machines. Most of the homes were built of typical concrete block construction, single/double block and externally rendered. All of the houses had operable windows, and all occupants had potential for visual contact with the outside. In the next section the energy efficiency potential of each home, and its actual energy performance are reviewed and the thermal experiences within the studied dwellings are discussed.

Moreover, tracing the behaviour of the mean indoor temperatures in the living and bed rooms of each dwelling in twenty-four hours' strings, Figure 3, demonstrate the range of temperatures experienced in the different homes vary significantly between the dwellings. The reasons behind these differences in what constitutes occupied, acceptable and reportedly uncomfortable internal temperatures are sought.

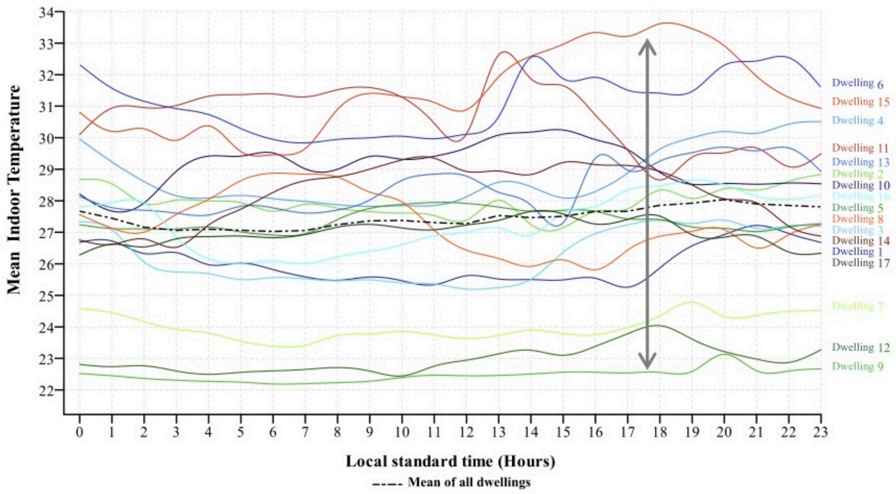

Figure 3 The traces of the mean indoor air temperature in the string of 24 hours in the studied Dammam's homes during August 2013

One of the most effective strategies for reducing domestic energy consumption and increasing occupant comfort was found to be simply the existence of a high performance dwelling envelope, with sensibly sized openings facing in a good orientation taking in requirements of heat gain and loss, lighting and air movement. Achieving both comfort and low energy consumption demonstrably benefits from 'whole system thinking', as they can be seen to result from the sum of many different building parts and behavioural and attitudinal attributes of the occupants. The main physical attributes that appear to determine performance most are discussed below individually and as clusters in the case study houses and include:

1. orientation
2. internal spatial planning
3. allocation and sizing of fenestration
4. day lighting and shading provision
5. cooling and ventilation strategies
6. construction materials

Table 2: The dwellings characteristics, the comfort survey result and electricity consumption details of the seventeen dwellings collected in Dammam during summertime 2013, arranged in ascending order of good house performance recorded in terms of energy consumption per meter square.

	Dwelling Number	Dwelling Type	Dwelling Age	Building Material	HVAC system	Dwelling Orientation	Double\Single Windows	Percentage of openings	Insulation	Mean T_a (°C)	ASHRAE	Annual bill £ / m^2	Energy kWh / m^2
Well behaviour homes	6	House	11	Concrete block	Fans, Central HVAC and AC Unit	NE	D	18.70%	Yes	30.4	1.4	1.9	89.3
	9	Apartment	20	Concrete block	Central HVAC	NE	D	7.70%	Yes	22.4	-0.6	1.1	90.9
	1	Apartment	10	Concrete block	Window AC and AC Unit	NE	D	10.80%	Yes	25.7	-1.1	1.1	95.1
	2	Apartment	10	Concrete block	Fans, Window AC and AC Unit	SE	D	N/A	Yes	27.2	-0.9	1.4	97.1
	17	House	2	Red bricks	Central HVAC	E	S	N/A	Yes	27.5	-0.6	1.5	101.2
	10	Apartment	5	Concrete block	AC Unit	N	S	N/A	Yes	26.7	0.5	1.1	101.4
	16	Apartment	12	Concrete block	Fans, Window AC and AC Unit	NE	D	19.90%	Yes	27.6	-0.4	1.3	104.1
↕	12	Apartment	15	Concrete block	AC Unit	SW	S	9.70%	Yes	23.1	0.4	1.6	106.5
	5	House	22	Concrete block	Central HVAC and AC Unit	SE	S	11.90%	Yes	27.5	-0.1	2.8	108.8
Badly behaviour homes	4	House	12	Concrete block	AC Unit	NW	S	N/A	No	28.7	0.4	1.8	111.7
	7	House	20	Red bricks	Central HVAC	SW	S	N/A	Yes	24.1	-0.3	2.3	118.7
	3	House	25	Concrete block	Window AC and AC Unit	NW	S	31.30%	No	26.8	-0.5	2.1	125.2
	14	House	4	Concrete block	Window AC and AC Unit	NW	S	N/A	No	28.1	0	1.7	125.9
	11	House	18	Concrete block	AC Unit	SE	S	N/A	No	28.6	0.4	2.9	148.3
	8	Apartment	15	Concrete block	Window AC	SW	S	45.80%	No	26.8	0.4	1.9	165.8
	15	House	28	Concrete block	Window AC and AC Unit	W	S	48.60%	No	31.5	1.8	4	201.7
	13	House	27	Concrete block	Window AC and AC Unit	W	S	31.10%	No	28.6	-0.1	3.9	206.4

5.1 Orientation

In the extremely hot climate of the Dammam region, southern and mainly western facing windows result in solar gain in the afternoon, evening and at sunset, times of day that coincides with the hottest external temperatures. Overheating of rooms facing south and west builds up gradually from noon onwards. A western/southern orientation was found to be the typically the most uncomfortable one for rooms in Dammam's homes. In this study, most dwellings appear to have been oriented with little or no consideration of orientation or attention to the solar radiation and the thermal context of the local micro-climate. It is clear in this study that the orientation of the dwelling plays a massive part of the dwelling's energy consumption. Not surprisingly, two of the highest performing dwellings in this study are oriented with their longer façade facing the North-Northeast, with around 90 kWh/m^2 energy consumption per annum. However, the seven most energy-intensive dwellings in this study are improperly oriented, with the annual consumption of these homes ranging from 118 kWh/m^2 to a maximum of 206 kWh/m^2 per annum.

Proper orientation demonstrably enhances a dwelling's indoor climate: for well-performing dwellings constraints, as in numbers one and nine, the orientation of the longer façade of the dwellings have a tremendous impact on the mean indoor temperatures and the average daily temperatures of these dwellings was below the neutral temperature found in this study. Properly oriented dwellings with bedroom windows facing between North and East had average daily temperatures of less than 25°C, apart from house number six where the preference of the occupant was to occupy warmer conditions. On the other hand, when a dwelling was improperly oriented, with its bedroom windows facing west, as in cases thirteen and fifteen, the indoor temperatures exceeded the neutral temperature by at least 3K.

5.2 Internal Space Arrangement

The internal layout and room arrangements is fundamentally affect the heat distribution within the spaces in the home. As the western façade is likely to receive maximum radiation at the hottest time of day, and in turn all spaces adjoining this façade will experience the maximum heat gain. A good example was found in dwelling number nine uses the buffer space adequately, with a reasonable internal layout. The closed hall space in the outdoor entrance buffers the guest room and the living room, and the location of the least used guest room to the south, leaving all the main bedrooms to the north, which has worked perfectly. Placing the lounge in the buffered middle of this apartment reduced discomfort, as it limited the heat gain to the most used room. However, the deliberate use of thermal buffering spaces was found in this study to be limited and, in fact, in some cases they were misused. Dwelling thirteen, for instance, has a massive entrance into the guest area oriented to the north, while the main bedroom lying to the west with a mean internal temperature in the evening in this room above 30°C.

A closer study of the design and room arrangements shows that there are a lot of wasted areas in most homes. It is clear that people have little understanding of the thermal and energy implications of room location and zoning. People lend more weight to the value of 'making a show' in front of their guests, rather than valuing their own comfort, wellbeing and energy economy in their own homes. In most of the dwellings in the current study, the *majlis,* or guest reception room, was hardly used throughout the year but its size and location significantly affected the internal layout and orientation of the rooms in the home, being treated as a priority to be displayed prominently to guests. In dwellings number eight and thirteen, the guest sections take up the best location in the houses, oriented to the north, and bedrooms were then oriented to the west and south, significantly increasing energy needed for cooling load those occupied rooms of the dwelling.

5.3 Opening Choices and Solar Access

In considering the orientation of the dwelling, the issue with most climatic impact is the orientation of the glazed openings. Most of contemporary dwellings in the Dammam region seem to be designed with large window openings and with relatively little attention given to the local climate. In fact, in some cases, a window was placed in every possible wall inside the rooms, which may prove to be completely unnecessary.

Windows typically have a higher conductance coefficient than the rest of the building envelope. Therefore, dwellings with a high glazing ratio have greater heat gain, compared to similar homes with a lower glazing ratio. Solar gain through large windows in summer can elevate a dwelling's indoor temperature well above the outdoor day or night temperature levels and thus cause intolerable conditions indoors and significant thermal stress, consequently increasing the building's cooling load to compensate for this poor design. In house number fifteen, for example, where the glazing ratio is around 49% of the façades area, the indoor temperature been found usually close to or sometimes higher than the outdoor temperature. There appears in this study to be a clear relationship between the amount of the window opening to wall ratio and energy consumption. The larger the window area is in the façade, the more intense the energy demand for cooling is in the dwellings. For instance, as the size of windows in homes one, five, six, nine, twelve and sixteen is very reasonable, that less than 20% of the façades area, the consumption was 90 - 108 kWh/m^2 per annum, being the lowest average consumption of all studied homes. Whereas in dwellings three, eight, eleven and fifteen where the ratio of window to façade wall area ranges between 31% to 49%, the energy consumption ranges between 125 and 206 kWh/m^2 per annum. Therefore, as one intuitively suspects, the homes with smaller areas of fenestration that are also well oriented, provide much better protection against heat gain during the day.

5.4 Daylight and Shading

It has commonly been assumed that daylight as a natural source of light can be used for the satisfactory illumination of rooms during the day. However, due to the adverse hot conditions from the intense internal heat and intolerable visual glare experienced in Dammam, adaptable shading used at different times of day and year is vital. The current study, however, found that the occupants do not use external fenestration shading at all and rely solely on internal blinds and curtains to just screen the internal glare.

Although not used in the most of the case study homes, trees to the eastern and western sides of the house could create a cooler environment around the dwelling as an alternative shading strategy for the home. Although all homes in Saudi Arabia are surrounded by set-back spaces behind walls, creating front, side, and rear yards, it appears that people do not have an interest in planting vegetation around their dwellings to provide shade. The occupant of dwelling number six, however, was very pleased with the planting and pergola he had completed in his house's yard and was very satisfied with the resulting outside environment. Therefore, with the right kind of soil and plants, and perhaps more importantly, with a sustainability-oriented user attitude, it is possible to grow plants properly for adequate passive shading of façades, potentially using grey water from the numerous showers often taken to do so.

5.5 Cooling and Ventilation Strategies

Installing, operating and maintaining an efficient AC system is considered to be more expensive, possibly prohibiting users from adopting optimal solutions. In house number thirteen, with the highest home energy consumption per square metre, an enormous amount, in Saudi terms, was paid for energy of £3.85/m^2 per annum. The occupant stated that they also spent an excessive amount of money maintaining the AC equipment, of around £400 every six months without the cost of failing parts, due to the fact of it being an inefficient type of AC system, set also in a poor house design. In dwellings number nine and one, the energy costs, for example, are £1.14 and £1.10 per annum, respectively. Taking into account the fact that these dwellings have among the top performance envelopes, these particular two homes also have efficient cooling systems that are periodically maintained with a maintenance contract of around £400 per annum without the cost of failing parts. Accordingly, it is likely that the very cheap operational cost is a result of an efficient AC system in a more highly-performing home.

Sleeping discomfort is a significant issue, exacerbated by high humidity, especially in homes like six and twelve with high indoor temperatures. Standard ceiling fans, however, can create a comfortable environment when temperature and relative humidity levels are high but within acceptable ranges. In house number six, for instance, the occupants were shutting down the air-conditioners for around 20 to 45 minutes every two hours in the day time, even when the indoor temperatures exceeded 29°C and operating the ceiling fan. This house, with its active occupants, was subsequently able to achieve the highest performance and least energy demand per square metre among the studied homes. Whereas in dwelling fifteen, that without ceiling fan, 85% of the sensation votes during bedtime were warm and hot sensation votes preferring much more cooling as the indoor temperature never goes as low as 28°C until 2am.

The number of operating hours / days required to achieve thermal comfort can be substantially reduced by careful design of homes. It has been found that the air-conditioning in a poorly-designed dwelling (cases eight, eleven, thirteen and fifteen) with an inefficient AC system remains in operation for around nine months through the year, three more months of operating the air-conditioning than in well-designed dwellings. Furthermore, the operation of fans may reduce the number of months of operating the AC system at night, when the outdoor temperature is tolerable with adequate air movement, like in homes numbers six, seven and twelve, the operation of the AC system is limited to six months through the year. Therefore, it is favourable to install fans in bedrooms and all living areas, which would significantly reduce the use of the cooling systems.

5.6 Energy Efficient Construction

Contemporary construction of residential buildings throughout Saudi Arabia is typically with reinforced concrete systems. Various types of concrete products are employed including concrete blocks, floor tiles and precast concrete. Walls in Dammam were found to be constructed with concrete brick of 20 to 25 cm thickness, with very high conductivity and insufficient thermal resistance. Insulating the mass externally, which would significantly improve performance, is seldom done in Saudi Arabia Most well-performing homes had an external wall thickness of 30cm, whereas almost badly-performing homes had an external wall thickness of 25cm or less, including the insulation, if available. Moreover, most of the studied Dammam's homes seemed to be constructed without benefiting from the available passive summer cooling so they act as a hot bridge rather than a coolth store. Dwellings built fifteen years or more ago had no insulation, except those with high income owners who could build their dwelling to a higher standard. Dwellings without insulation in this study consumed 125kWh/m2 up to 206kWh/m2whereas all the better-behaved homes had insulation installed.

6 Conclusion

This study has shown that people in the selected homes in Dammam occupied mean indoor air temperatures widely ranging between 20°C to 35°C. The thermal sensation votes reported demonstrated that people largely adapted to be more or less comfortable in the temperatures they occupied. A survey of occupant's behaviours showed that adaptation was achieved through a range of attitudinal adjustments, behaviours and actions including the use of fans and AC systems and the opening of internal doors and to a lesser extent in summer, windows at different times of day and year.

Perhaps the most useful finding of the work is the extent to which the physical design and construction of the building itself is instrumental in determining the comfort and quality of life of the occupants of the homes. In most cases, the existence of well-oriented, high performance envelopes and internal thermal buffer spaces result in lower energy running costs and higher reported comfort levels. Buffering of living areas from the worst extremes of this often very hot climate was shown to improve comfort levels experienced in the homes. In some cases, the occupant's comfort was compromised by the desire to provide impressive guest facilities in homes. Good client briefing on design priorities and their impact on comfort and energy use is needed and the benefits of, for instance, smaller and fewer windows and good orientation promoted. Modification of the external environment of a home by creating an external thermal buffer zone, for example the shading of outdoor areas and walls of a home with trees, showed a positive effect on the energy consumption in the adjacent home. The highest performing homes had higher levels of insulation. Although the energy consumption in the dwellings was not clearly linked to the indoor temperature experienced in them, occupants who pay less per annum were more satisfied with the thermal comfort experienced. Comprehension of what creates and enables comfort to be experienced in the studied dwellings is undeniably a complex phenomenon. While clear connections between the physical condition of the buildings and their services and the indoor thermal environment are evident, however attitudes, social contexts and associated behaviours appear to be leading factors in the recorded occupied temperatures in these homes, and in turn to the everyday comfort, and discomfort, experienced in them.

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